REPORT No. 46.

A STUDY OF AIRPLANE ENGINE TESTS.

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RÉSUMÉ.

This report is a study of the results obtained from a large number of tests of an Hispano-Suiza airplane engine in the altitude laboratory of the Bureau of Standards. It was originally undertaken to determine the heat distribution in such an engine, but many other factors are also considered as bearing on this matter.

So many variables enter into the testing of multicylinder internal combustion engines that even where every effort has been made to keep conditions constant the results of a large number of tests must be studied in order to reach sound conclusions. This has been done in the present case. Graphical methods of expressing the various relations have been used where possible, and the results plotted in a wide variety of ways to check their accuracy. The use of logarithmic coordinate paper has permitted the plotting of many of the relations as straight lines.

Considering the tests as a whole, there are three major variables: Speed, altitude, and horsepower. Temperature during the tests was maintained practically constant. The loss in power through friction was assumed constant at any given speed regardless of altitude. This appeared to be justified, as will be described later. Indicated horsepower has been considered as brake horsepower plus friction horsepower. Indicated horsepower appears to decrease in direct proportion to decrease density of the air. Its decrease with increase in altitude is due only to the fact that a variation in altitude necessarily implies an increase or decrease in density. For a given temperature, density is directly proportional to barometric pressure. Hence, the graphical representation of the variation of indicated horsepower with barometric pressure, when plotted on logarithmic coordinates, will be a straight line whose slope is unity.

A study of the heat distribution under the various conditions shows that:

(1) The brake thermal efficiency remains constant at about 24 per cent on the ground at all speeds. As the altitude is increased its value drops to about 20 per cent; the maximum value at altitudes occurring at a speed of about 1,600 r. p. m. The indicated thermal efficiency remains nearly constant at 26 per cent for all speeds and altitudes.

(2) The heat lost in the exhaust is at a maximum at 1,900 r. p. m. at all altitudes, and amounts to almost 50 per cent of the heat supplied on the ground, decreasing to about 40 per cent at 30,000 feet altitude.

(3) The heat lost through friction varies from 2 per cent at 1,700 r. p. m. and 3 per cent at 2,100 r. p. m. on the ground to 6 and 8 per cent, respectively, at 30,000 feet altitude.

(4) The heat lost in the jacket water is about 17 per cent of that supplied at all speeds on the ground, increasing to 28 per cent at 2,100 r. p. m. and 35 per cent at 1,300 r. p. m. at 30,000 feet.

Due to the fact that the heat supplied in the gasoline varies with altitude, the above percentages are not absolutely accurate. The heat supplied appears to be proportional to the density of the air up to about 10,000 or 15,000 feet altitude. As the density is further decreased relatively more gasoline is necessary and the proportionality between heat supplied and density ceases. The heat utilized and lost appears to follow about the same relation as the heat supplied.

Fuel consumption varies from a minimum of 0.50 pound per B. H. P. per hour on the ground to a maximum of 0.69 at 30,000 feet.

The study of the relation between power and speed shows that the increase in power through increase of speed is at a maximum on the ground; the gain becoming less as the altitude is in-

creased, until at 30,000 feet there is practically no gain in power with increase in speed above about 1,700 r. p. m. After reaching a sufficient altitude, the curves show that the engine would stall at from 450 to 500 r. p. m., with wide-open throttle, as there would not be sufficient power to overcome the friction losses.

The power lost in friction is a very important factor in the performance of the engine at high altitudes. While its value can not at present be determined with extreme accuracy, owing to the fact that no satisfactory indicator for high-speed internal-combustion engines is now available, a careful investigation was made of all the data bearing on this question. After carefully considering these results and the fundamental laws governing the subject, it is concluded that friction mean effective pressure is practically a constant for a given speed and is independent of altitude.

Considering the matter of carburetion, the results indicate that the optimum proportion of gasoline to air for maximum fuel economy is not a constant at constant speed with change in altitude. Apparently the leanest mixture could be used at about 15,000 feet with greater weight proportions of fuel to air at other altitudes.

SUMMARY OF CONTENTS.

INTRODUCTION.

This work was undertaken, primarily, to study the distribution of heat in an internal-combustion engine, such as is used for airplanes. The energy supplied to the engine per unit of time can be accurately determined by weighing the gasoline supplied and determining its calorific value. Likewise, the measures of the energy delivered at the brake, the heat rejected in the exhaust, and the heat removed by the jacket water, can be readily ascertained. The amounts of energy lost in overcoming friction, in drawing in and compressing the charge, and in expelling the products of combustion, are not measurable by any direct means at the present time. The future may bring forth an indicator suitable for high-speed internal-combustion engines, but there is none at present. The power required to drive the various pumps and the magneto could be, but have not been, determined. All of these unknown losses have here been lumped together and called friction.

In order to obtain an idea of the magnitude of the friction losses, the assumption was made that the force driving the piston is directly proportional to the weight of the charge in the cylinder. Thermodynamic and "indicated" thermal efficiencies are dependent upon compression ratio, not upon absolute compression pressures. The consistent results and the checks obtained seem to justify this assumption.

In testing multicylinder internal-combustion engines there are so many factors that influence the operation of the engine that the results of two tests under apparently the same conditions may not agree as closely as would be expected by a person accustomed to testing steam engines or turbines. A few of the many variables that may affect the results of tests of internal-combustion engines are: Temporary or permanent valve leakage due to carbon deposits or warping; lubrication changes, slight changes in carburetion due to temperature effects or humidity; alteration in ignition by change of spark gap, electrical leakage of porcelain, or by preignition; changes in weight of charge due to change of temperature of piston and cylinder walls, although jacket water was so regulated as to leave the engine at about 140° F. in all tests; etc.

Of these possible variable factors, lubrication was maintained as constant as possible by the use of a uniform grade of oil and by maintaining the oil temperature as uniform as was practicable. Air temperatures were maintained within a rather narrow limit except at ground level. Humidity was not controlled but for all observations at other than ground level, the humidity was extremely low due to precooling of the air. Spark-plug gaps were carefully maintained constant and extreme care was exercised to avoid all irregularities of ignition, including preignition.

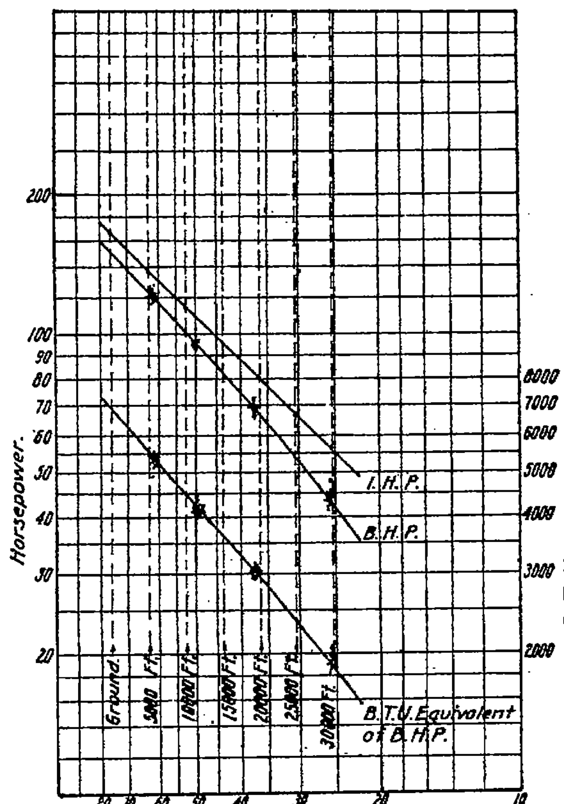
In spite of the care exercised to secure uniform conditions, it is necessary to average a large number of tests in order to determine the general laws and the fundamental relations of the variables. Graphical methods were given preference over other methods. If any desired relation can be shown by a straight line, then the method of averaging by plotting the data is exceptionally reliable. It was found that any one small group of tests was liable to lead to conclusions slightly at variance from the average of the whole, and it is advisable to consider, together, all tests under similar conditions.

Because of the conditions outlined above, the results of these tests, 390 in number, were graphically analyzed in nearly as many different ways as could be thought of: Plotting, cross-plotting, and replotting the various items. This method of handling furnished somewhat of a check on the truth of the necessary assumption. It also makes strict search into the accuracy and consistency of the handling of the data.

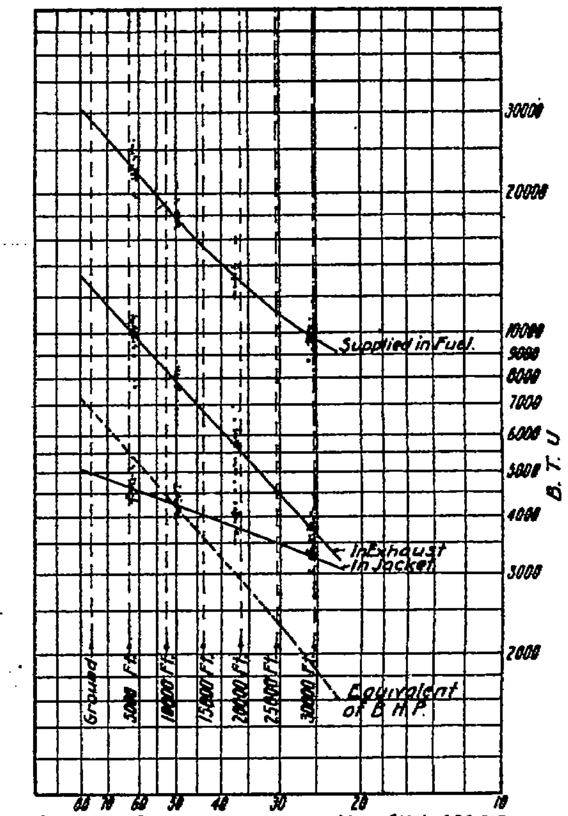
I. AVERAGING THE TESTS.

The Hispano-Suiza engine upon which these tests were made was a stock airplane engine rated 180 horsepower at 1,700 r. p. m., with 8 cylinders 4.72 by 5.12 inches, arranged in a 90° vee, with compression ratio of 5.3 to 1. The engine was tested in the altitude chamber with barometric pressures such as are normally associated with altitudes of about 5,500, 11,500, 19,200, and 29,500 feet, but with nearly constant temperature of about 0° F., on all tests. At each "altitude" tests were made with speeds of about 1,300, 1,500, 1,700, 1,900, and 2,100 revolutions per minute, the change of speed being secured by change of load on the Sprague dynamometer, with throttle wide open on all tests. The carburetor was a Claudel, and the proportion of gasoline to air was adjusted to give maximum power on the lean side for each test. One grade of gasoline (called X) was used for 171 tests, and nine other fuels were used during the other 219 tests. The X gasoline was used as a standard, for the purposes of comparisons, in all of the seven groups into which the tests were divided. It was found that the variations in results using X gasoline were of the same order of magnitude as the variations between X gas and the other fuels. Hence all of the data, irrespective of fuel, taken under similar operating conditions, were plotted together.

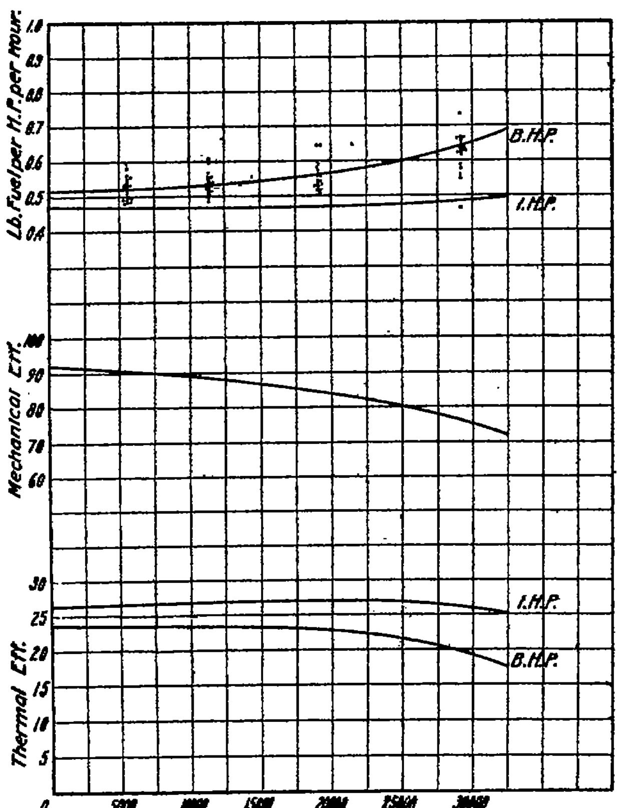
Looking at the tests as a whole, there are three major variables—speed, altitude, and horsepower. The relation between altitude and power, taking the various speeds separately was the first selected for study.



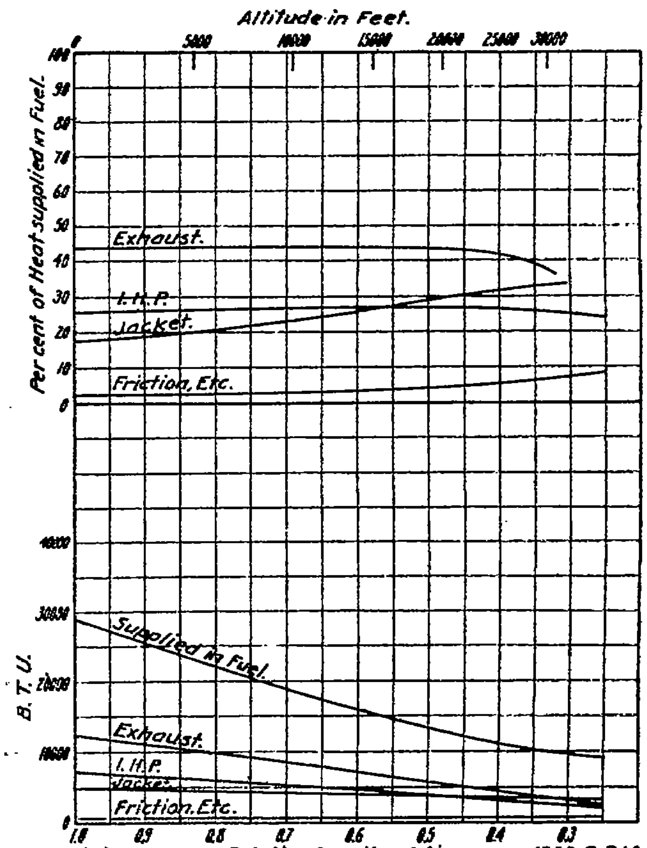
Plot No. 1a. Barometric Pressure (Cm. of Hg.) 1300 R.P.M



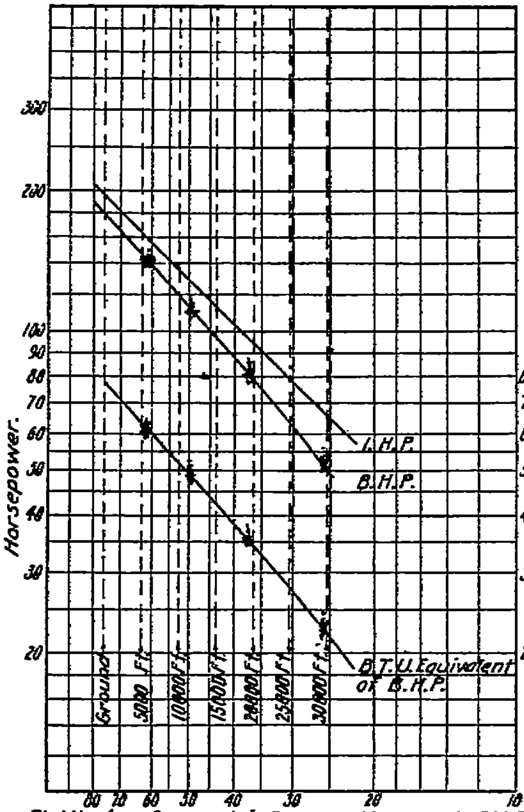
Plot No. 1b. Barometric Pressure (Cm. of Hg.) 1300 R.P.M.



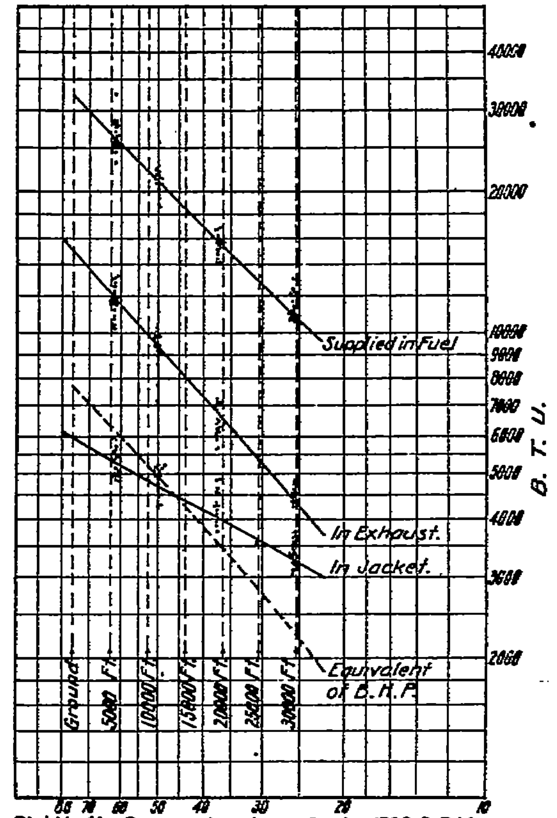
Plot No. 2 Altitude in Feet. 1300 R.P.M.



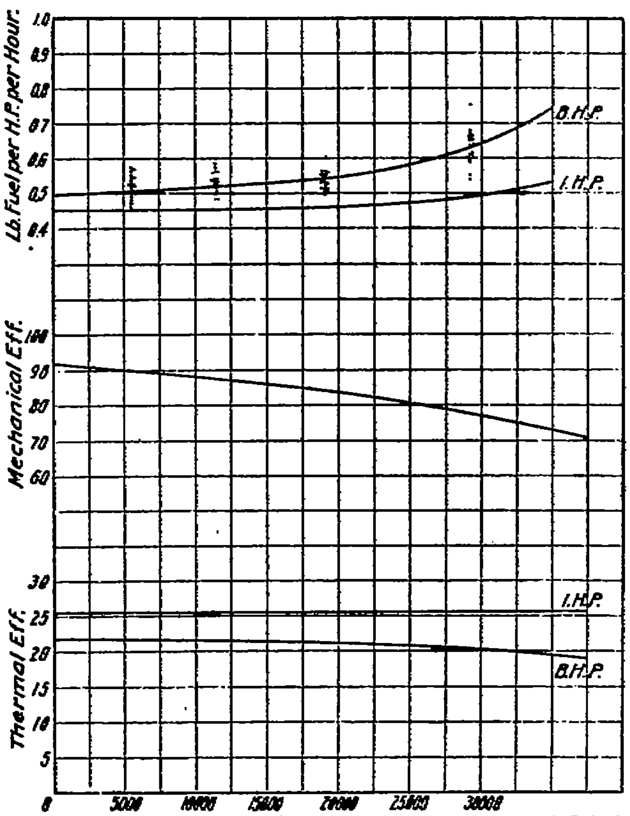
Plot No. 3 Relative Density of Air 1300 R.P.M.



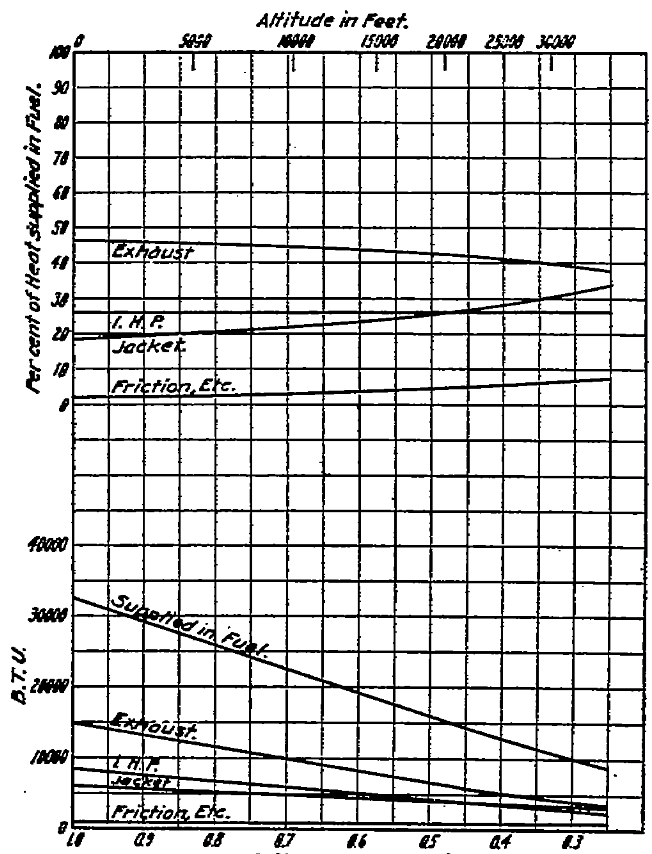
Plot No. 4a. Barometric Pressure (Cm. of Hg.) 1500 R.P.M.



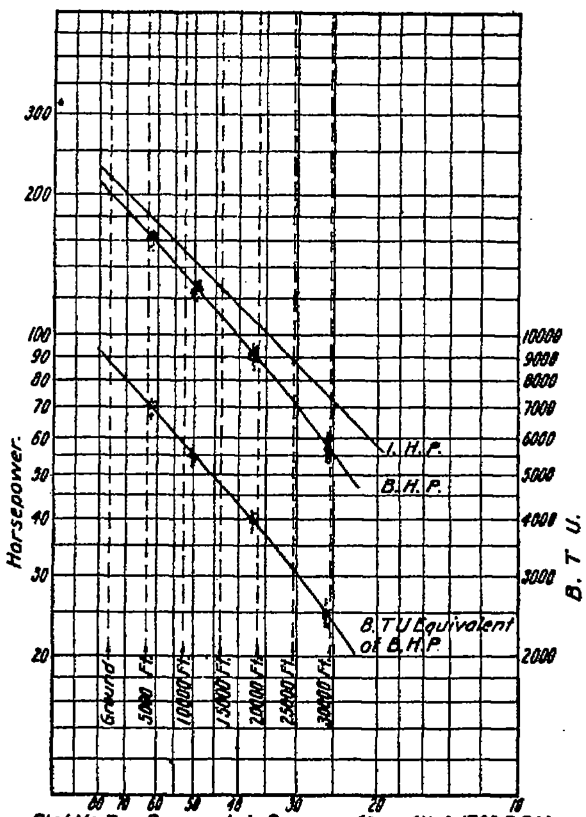
Plot No. 4b. Barometer. (Cm. of Hg.) 1500 R.P.M.



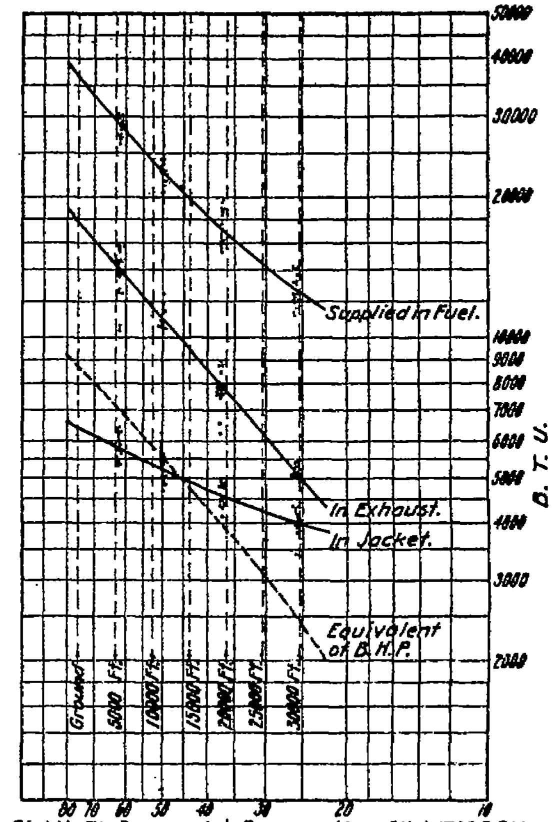
Plot No. 5 Altitude in Feet. 1500 R.P.M.



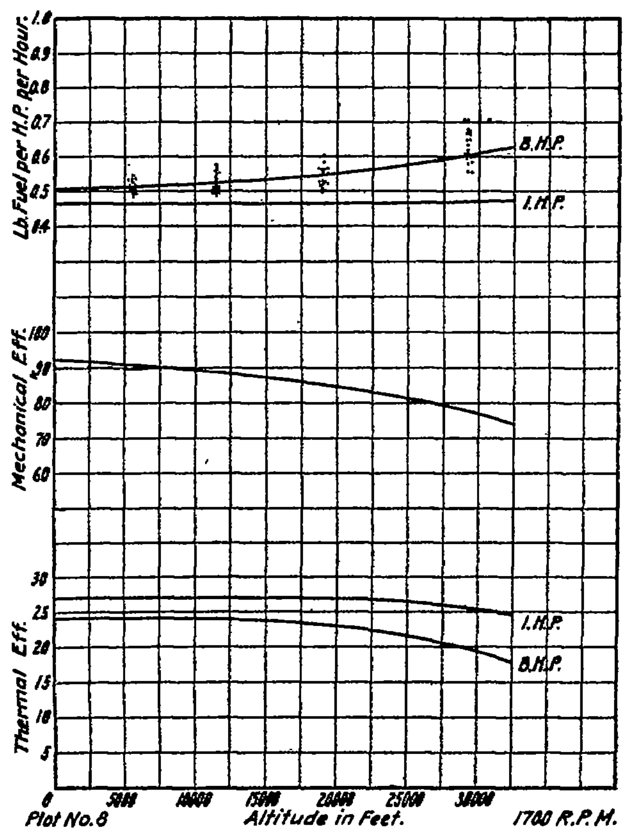
Plot No. 6 Relative Density of Air. 1500 R.P.M.



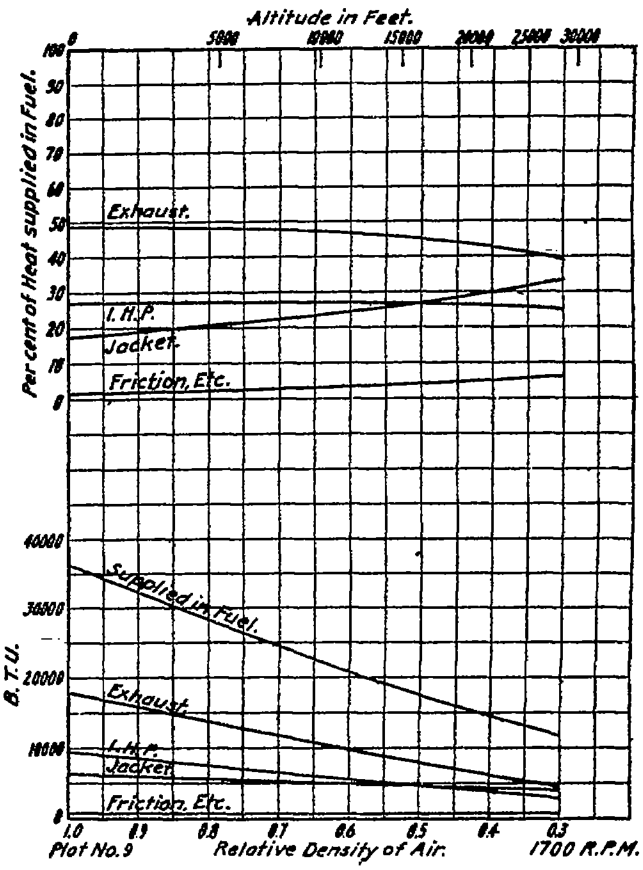
Plot No. 7a Barometric Pressure (Cm. of Hg.) 1700 R.P.M.



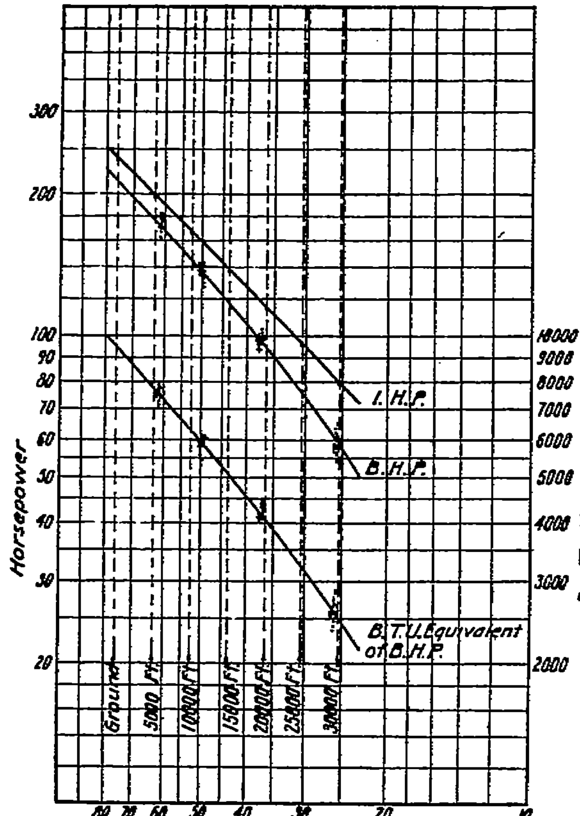
Plot No. 7b Barometric Pressure (Cm. of Hg.) 1700 R.P.M.



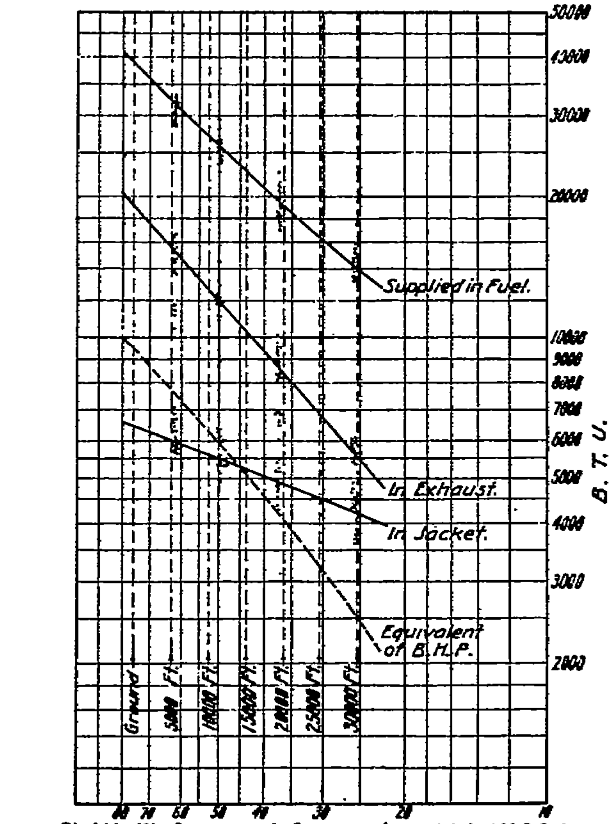
Plot No. 8 Altitude in Feet. 1700 R.P.M.



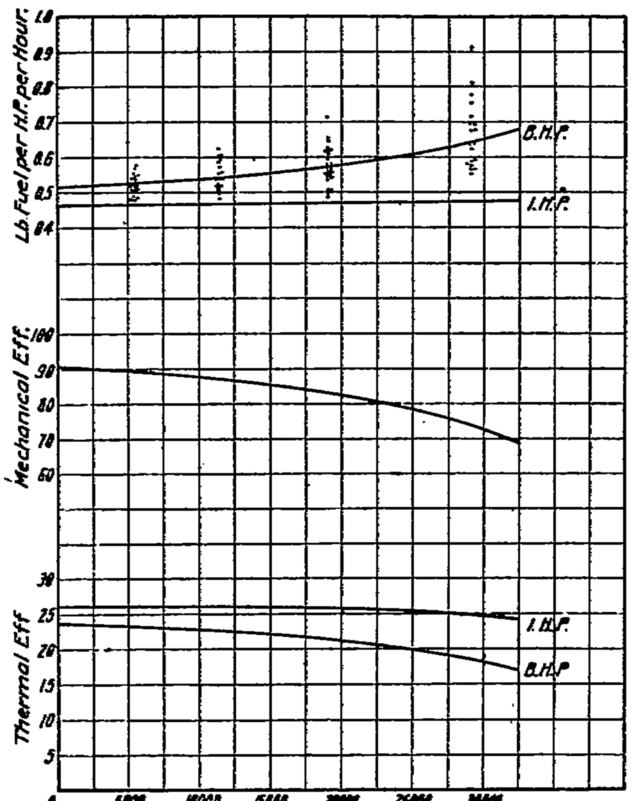
Plot No. 9 Relative Density of Air. 1700 R.P.M.



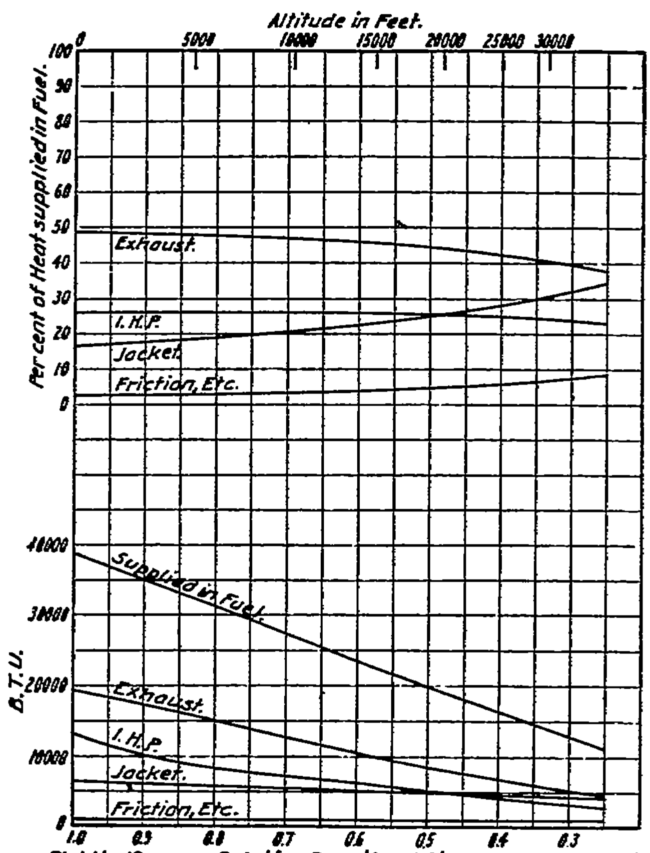
Plot No. 10a. Barometric Pressure (Cm. of Hg) 1900 R.P.M.



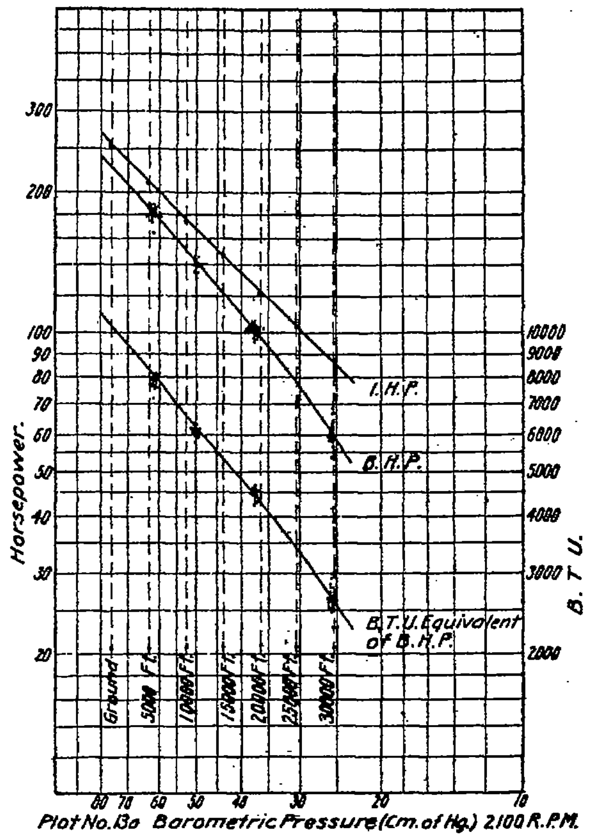
Plot No. 10b. Barometric Pressure (Cm. of Hg) 1900 R.P.M.

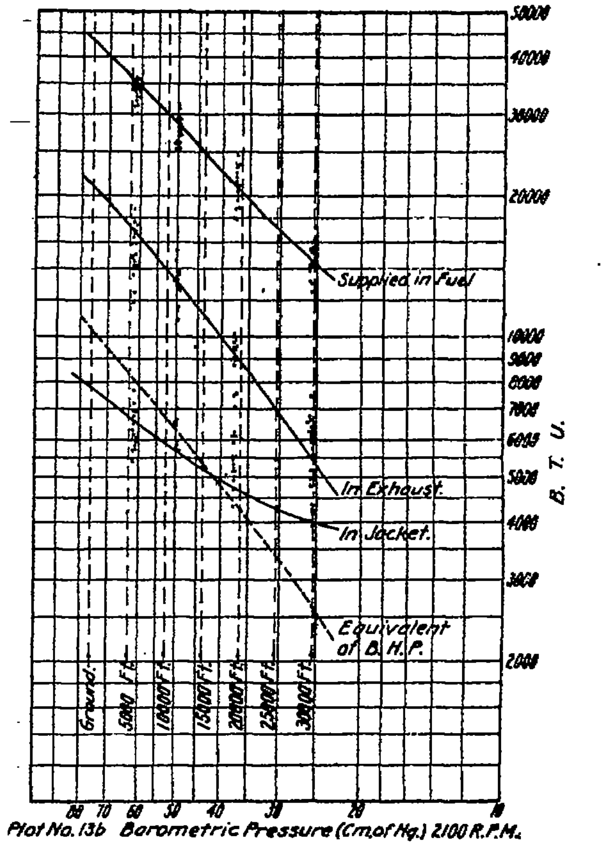


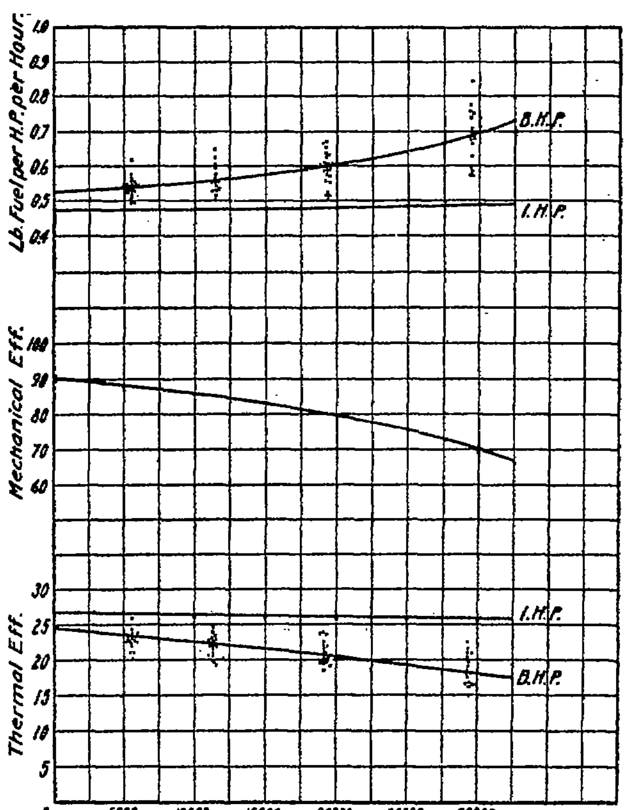
Plot No 11 Altitude in Feet 1900 R.P.M.

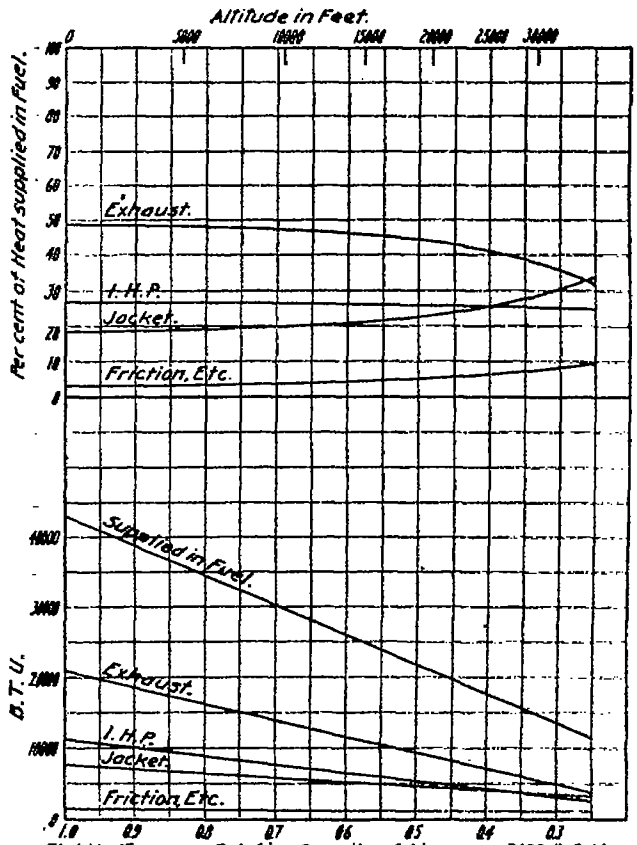


Plot No. 12. Relative Density of Air. 1900 R.P.M.


Horsepower.
B. T. U.
I.H.P.
B.H.P.
B.T.U. Equivalent of B.H.P.
Ground
5000 Ft.
10000 Ft.
15000 Ft.
20000 Ft.
25000 Ft.
30000 Ft.
Plot No. 13a Barometric Pressure (Cm. of Hg.) 2100 R.P.M.


B. T. U.
Supplied in Fuel
In Exhaust.
In Jacket.
Equivalent of B.H.P.
Ground.
5000 Ft.
10000 Ft.
15000 Ft.
20000 Ft.
25000 Ft.
30000 Ft.
Plot No. 13b Barometric Pressure (Cm. of Hg.) 2100 R.P.M.


Lb. Fuel per H.P. per Hour.
B.H.P.
I.H.P.
Mechanical Eff.
Thermal Eff.
I.H.P.
B.H.P.
Plot No. 14 Altitude in Feet. 2100 R.P.M.


Altitude in Feet.
Per cent of Heat supplied in Fuel.
Exhaust.
I.H.P.
Jacket.
Friction, Etc.
B.T.U.
Supplied in Fuel.
Exhaust.
I.H.P.
Jacket.
Friction, Etc.
Plot No. 15 Relative Density of Air. 2100 R.P.M.

With an engine running at constant speed, if the weight proportion of fuel to air is unchanged, the weight of charge drawn into the cylinder will be directly proportional to the density of the air. The power developed by the burning of the charge (indicated horsepower) will decrease in direct proportion to the density. For a given temperature, the density is directly proportional to the barometric pressure. The relation between altitude and barometric pressure is—

$$\text{Altitude} = \text{Constant} \times \log \frac{\text{Barometric pressure at ground.}}{\text{Barometric pressure at altitude.}}$$

These tests were made at nearly constant temperature, hence if the indicated horsepower for a constant speed is plotted as ordinates and the barometric pressure is used as abscissae upon cross section paper having logarithmic instead of arithmetic spacing, the relation should be a straight line with a slope of unity. The brake horsepower would differ from this only by the mechanical and pumping losses of the engine. The values of brake horsepower at the various altitudes are plotted in this manner on plots 1, 4, 7, 10, and 13, each for a different speed. The relation is a slightly curved line, suggesting an equation of the form:

B. H. P. – (a constant friction H. P. for each speed) = I. H. P.

Generalizing upon the matter of the friction horsepower for any one speed, it would seem reasonable that it should be nearly a constant. The fluid pumping losses, the power required to drive the magneto, the pumps, and the valve gear should change little, if any, with change of altitude. The bearing friction loss is of the form:

Total friction = (constant × load) + (constant × viscosity × speed). For the present the case of constant speed has been selected. Viscosity may increase with increase of altitude because less heat is generated in the engine at greater altitudes. An increase of viscosity will increase the friction loss. The load factor in the friction equation is an unknown, in the sense that it is a composite of inertia and gas pressure factors, whose relation changes with design, speed, altitude, etc. The pressures on the bearings may or may not reverse in direction. However, a large change of bearing pressure will cause only a comparatively small change of total friction. On the whole, the bearing friction is a small part of the mechanical losses of the engine, and may be assumed constant. The piston friction is probably the largest single item of all the losses, and apparently will be nearly constant for a given speed, depending more upon inertia forces than upon fluid pressures.

Therefore the assumption was made that the friction horsepower is constant for a given speed. Combining with this one the other assumption, or fact, that the I. H. P. is directly proportional to the density of the air, use was made of the fact that

$$BHP + FHP = IHP.$$

Two values of B. H. P. were read from one of the curves, plots 1, 4, 7, 10, and 13, corresponding to any two altitudes. One of the unknown quantities, I. H. P., was multiplied by the relative densities at the two altitudes. The other unknown, the F. H. P., was thus found by algebraic means. This was repeated, using other altitudes, and a general mean of the F. H. P. for a given speed was thus determined. This value of F. H. P. was then added to the B. H. P. curve values, the I. H. P. values thus obtained were plotted, and a straight line with unity slope (45° on this log scaling) was drawn through the points. The fact that the straight line with unity slope does pass through the points indicates that the two assumptions stated above are not inconsistent. Reading from these I. H. P. and B. H. P. curves, the I. H. P. and B. H. P. values were recorded in Table 1 for altitudes of 0 (ground), 5,000, 10,000, 15,000, 20,000, 25,000, and 30,000 feet.

The test results of heat units (B. t. u.) supplied in the fuel per minute, discharged in the exhaust gases and in the jacket water, as well as the B. H. P. expressed in B. t. u., are plotted on the same plots as the B. H. P. The numerical values of these items tabulated in Table 2 were read from the curves. The test results on fuel consumption were plotted on arithmetically scaled coordinates on plots 2, 5, 8, 11, and 14, together with the mechanical and thermal efficiencies as derived from the curves on plots 1, 4, 7, 10, and 13.

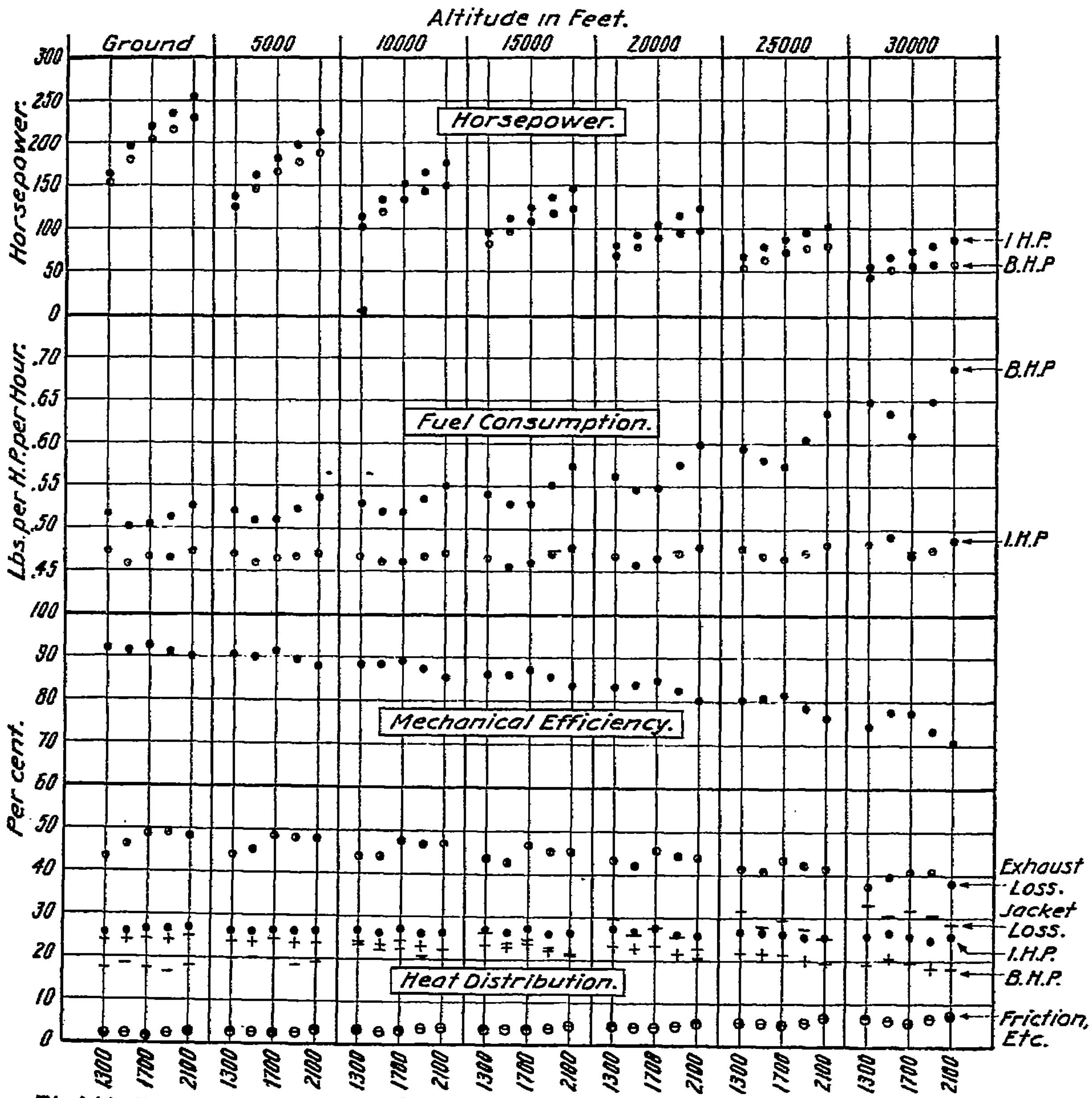
By using relative density of air instead of altitude, many of the relations can be changed from sharp curves to nearly straight lines. As a matter of fact, the density is the controlling variable, altitude enters only because of the density associated with it. The heat distribution at the several speeds, plots 3, 6, 9, 12, and 15, are plotted in this way, using relative density as abscissæ with an altitude scale superposed. One set of curves shows the quantity of heat in B. t. u. as ordinates, which was supplied in the gasoline, utilized in the I. H. P., rejected in exhaust, and absorbed in jacket water. The other set gives the same items in per cent of the heat supplied in the fuel (gasoline).

The heat distribution results of the 2,100 r. p. m. group were first worked up by plotting the percentage of heat accounted for in the various items, as originally computed on each test. In fairing the curves an effort was made to keep the total per cent heat accounted for down to as low a value as possible, consistent with the data. Later the curves thus obtained were superposed on the plotted points of the test values, plotted as in the other speed groups, and were found to agree quite well. For the other speed groups the heat distribution was studied by plotting heat units instead of percentages. This statement will explain why the 2,100 r. p. m. totals of "Heat accounted for" (Table 2) are somewhat lower than those of the other speeds. The difference is greater at the higher altitudes. The results for other speeds are obtained in the more logical manner. It hardly seems possible that so much of the heat supplied could be accounted for in the observed items of the tests as shown in Table 2. Surely there is considerable conduction, convection, and radiation of heat from the engine which was not measured. The exhaust gases were not analyzed, but undoubtedly they contained some unburnt gasoline and some products of incomplete combustion. How much heat energy is supplied in the lubricating oil is, of course, unknown; but the oil consumption of airplane engines runs somewhere around 6 to 7 per cent of the volume of gasoline, or 8 to 9 per cent by weight. The heating value of the lubricating oil is substantially the same as gasoline, about 20,000 B. t. u. per pound. Some portion of this oil consumption must be burnt with the gasoline. Perhaps it might be well to consider that the heat supplied in the fuel should be 3 to 5 per cent greater on account of the oil than is shown by the gasoline measurements. In case the heat in the exhaust is measured by the rise of temperature of a known weight of water which is mixed with and cools the exhaust gases, it is obvious that the higher heating value of the fuel must be used in computing the heat supplied. In these tests the higher value was used and correction was made for water vapor in the exhaust. When the lower heating value of the fuel is used, the engine is not credited with receiving all the energy which is actually supplied. The exhaust calorimeter measures this heat, because it condenses most of the water formed by the burning of the hydrogen of the fuel. The amount of heat thus charged against exhaust and not credited as supplied would be about 6 to 8 per cent with gasoline fuel (depending upon which one of the many lower heating values is used).

II. GRAPHICAL PRESENTATION OF HEAT DISTRIBUTION AND ENGINE CHARACTERISTICS.

Reading values from the curves drawn through the plotted points of test results for the speeds of 1,300, 1,500, 1,700, 1,900, and 2,100 r. p. m. and for altitudes of ground 5,000, 10,000, 15,000, 20,000, 25,000, and 30,000 feet, the I. H. P.'s, B. H. P.'s, and fuel consumption per B. H. P. hour were tabulated on Table 1. In this table are also given other results of the graphical analyses: Mechanical efficiencies (B. H. P. ÷ I. H. P.), F. H. P. (as originally computed; also I. H. P. minus B. H. P.); fuel consumption per I. H. P. per hour, the relative "indicated" torque, relative friction torque, and the brake torque as derived from original data on plots 22 and 23. In a similar manner the values of the heat distribution are assembled in Table 2, on both a B. t. u. and a percentage basis, as well as the total per cent accounted for. The last was obtained by adding together the brake thermal efficiency and the per cent heat lost in exhaust, in jacket water, and in friction for each speed and altitude. Using the values from these tables, the data were assembled and plotted on the basis of r. p. m. as abscissæ, each altitude treated in a separate curve, plots 16 and 17. The three major variables entering into the engine performance are power, speed, and air density. The original plotting of the data considered the variation of power with density for constant speeds. If points are read from these curves, and plotted as power versus speed for constant densities, the result should be a smooth curve. If the three variables are plotted on three dimensions, a smooth surface should result. (See Plot 18.) By plotting in this manner, if the points are consistent with each other, it means not only that the data were consistent, but also that the various speed groups were handled alike in the graphical analyses.

The brake thermal efficiency, plot 16 (based on power delivered), remains constant at about 24 per cent on the ground through speed changes of from 1,300 to 2,100 r. p. m. As the altitude is increased, the brake thermal efficiency drops to about 20 per cent, showing a maximum value at about 1,600 r. p. m. and with a tendency to decrease more rapidly with increase than with decrease of speed from this "best speed."

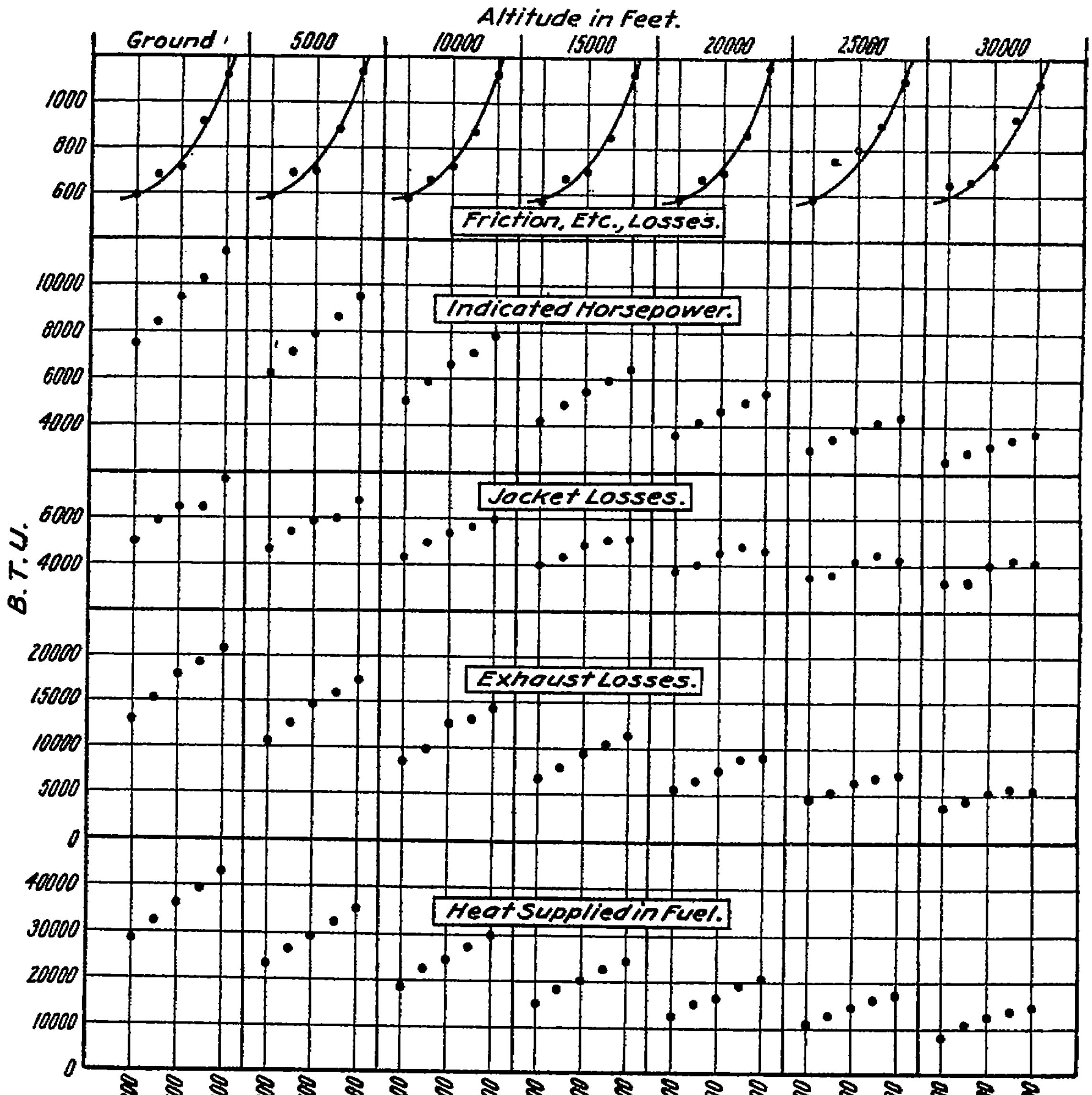


Plot No 16

The "indicated" thermal efficiency, plot 16 (based on B. H. P. plus friction, as equivalent to the horsepower that should be shown by an indicator card), remains nearly constant at about 26 per cent for all speeds and altitudes. There may be a tendency for the indicated thermal efficiency to increase with increase of speed at the ground, reversing to a decrease of efficiency with increase of speed at 30,000 feet. This is not shown definitely enough at present, as such tendency is hardly more than an allowable difference.

The heat discharged in the exhaust, plot 16 (found by bringing the exhaust gases back to their original temperature and measuring the heat absorbed, neglecting unburnt and incompletely burnt fuel), is at its maximum percentage at 1,900 r. p. m. at all altitudes. It is almost 50 per cent of the heat supplied when on the ground, decreasing to about 40 per cent at 30,000 feet.

The percentage loss in friction, plot 16, drops very slightly as the speed is increased from 1,300 to 1,700, where it is a minimum at all altitudes, increasing again more rapidly as the speed is increased above 1,700 r. p. m. At a given speed an increase of altitude causes an



Plot No. 17.

increase of the percentage heat wasted in friction. Friction takes 2 per cent of the heat supplied when the engine is on the ground and turning over at 1,700 r. p. m. At 30,000 feet, 6 per cent is wasted, at the same speed. At 2,100 r. p. m. for the same altitude change, the increase is from 3 to 8 per cent.

In making the tests, the jacket water, as it left the cylinders, was constantly kept at about 140° F. A change of this temperature would certainly change the percentage values for exhaust losses and for thermal efficiencies. Perhaps friction would be altered, to a minor extent, through change of viscosity. The engine pumping work might also be slightly changed. As operated, the jacket heat loss on the ground, in per cent, is about constant at 17 per cent, through the speed changes. As the altitude is increased the percentage increases at all speeds and becomes a variable with speed for altitudes, so that at 30,000 feet altitude it is 35 per cent at 1,300 r. p. m., dropping to 28 per cent at 2,100 r. p. m.

Because of the change in amount of heat supplied in the gasoline, increasing with speed and decreasing with altitude, the percentage basis does not give a complete showing of all the variations. On plot 17 it is seen that the heat supplied increases (apparently) directly with increase of speed at the ground. At 30,000 feet it approximates this relation up to around 1,500–1,700 r. p. m., but a further increase of speed is not associated with as great an increase of energy supplied. From the curves on plots 1, 3, 4, 6, etc., for constant speeds, it is seen that the heat supply is proportional to the density of the air, up to about 10,000 or 15,000 feet; then, as the density decreases, relatively more gasoline is necessary, and the proportionality between density and heat supply ceases. This can also be indirectly seen from other curves, and will be taken up more fully later on. Apparently the change can not be charged entirely to carburetion.

The heat (B. t. u's.) lost in the exhaust, in the jackets, and utilized in indicated horsepower seem to follow, in a general way, the same relations with speed and with altitude as those indicated for the heat supplied.

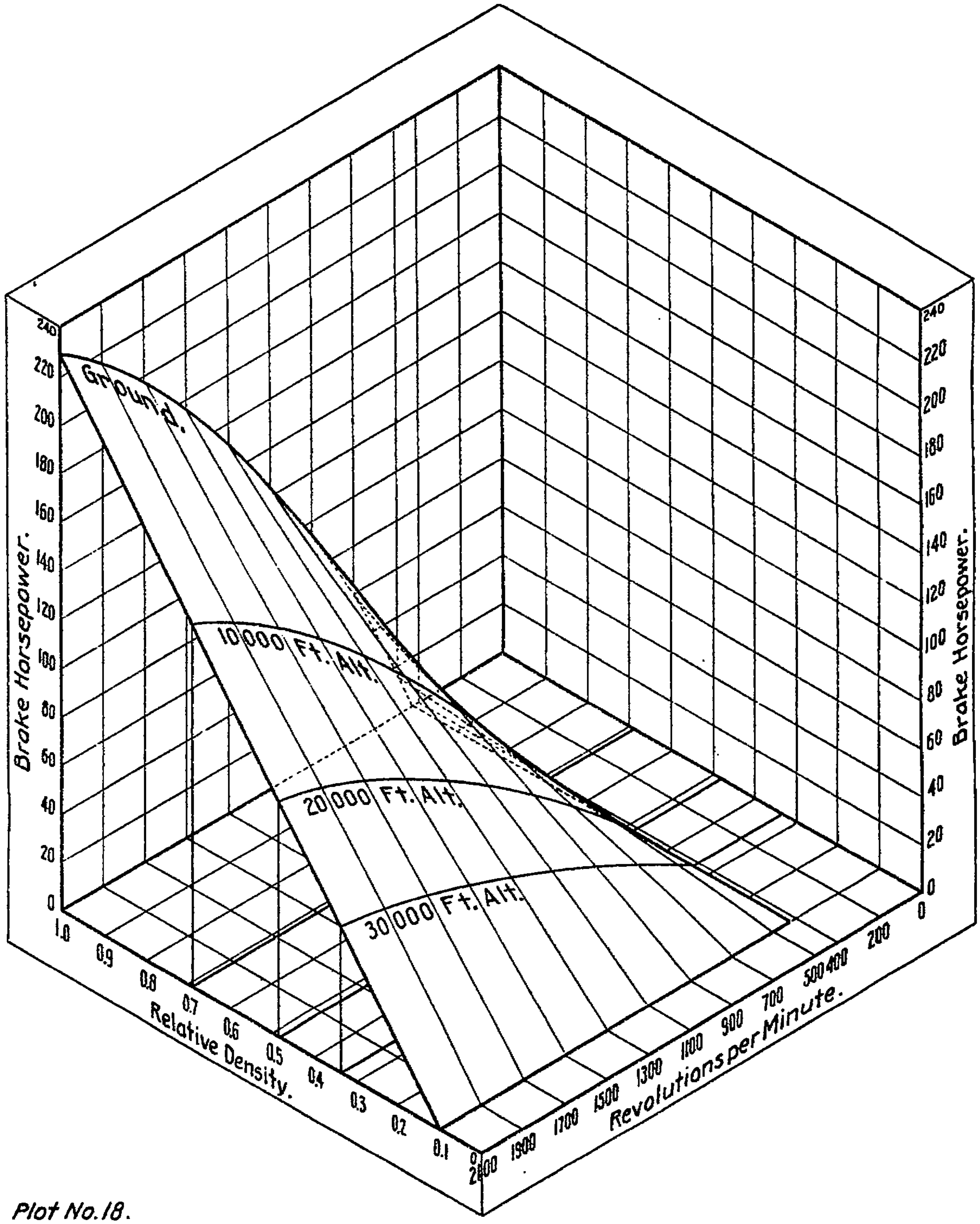
The friction losses shown on plot 17 are shown to such an open scale of B. t. u. that the internal variations are apparently large, although really they are relatively small. Exactly the same curve has been drawn through the points for each separate altitude, and it seems to fit all of them equally well. From this it may be deduced that altitude does not directly affect the friction losses. The basic assumptions are that the indicated power of an engine is proportional to density, and that the friction loss for a given speed is nearly independent of the density. The fact that this one curve does fit all the independently computed points is a sort of indirect evidence that the two assumptions are at least fairly consistent. Later an attempt will be made to check this assumption by indirect means.

On plot 16 are plotted the tabulated values of mechanical efficiency. This is found to be a maximum at about 1,700 r. p. m. for all altitudes. At ground level it is nearly constant at 92 per cent for speeds from 1,300 to 1,700 r. p. m., falling off to about 90 per cent at 2,100 r. p. m. As the altitude increases, the mechanical efficiency decreases, until at 30,000 feet the tests show about 74 per cent at 1,300 r. p. m., rising to 77 per cent at 1,500 to 1,700 r. p. m., falling to 70 per cent at 2,100 r. p. m. There may be a tendency for the point of maximum mechanical efficiency to be at lower speeds at the higher altitudes, although this is only shown as a possibility. It is perfectly evident, however, that the effect of speed change upon mechanical efficiency is small at ground, but at high levels it is very marked, and the efficiency will rapidly fall off when the speed is altered from the optimum. According to Prof. G. B. Upton, "Airplane performance determined by engine performance," Sibley Journal, June, 1918, pages 137–142 (reprinted in S. A. E. Journal, October, 1918), the mechanical efficiency, as a function of altitude, is represented by

$$\frac{\textit{Density—Constant}}{\textit{Density}}$$

The constant for a given engine is density at ground $\times$ (1 − mechanical efficiency at ground). Applying this to the results of these tests (Table 1), it is found that when the mechanical efficiency at ground is 0.915, the efficiency to be expected at 30,000 feet is 0.726. The arithmetic average of the tabular values at ground is 0.915 ± 0.012, and at 30,000 feet is 0.745 ± 0.040. This checks within the accuracy of the methods and data used.

The fuel consumption, in pounds per horsepower per hour, both for I. H. P. and B. H. P., is also plotted on plot 16. When based on B. H. P. the effect of change of mechanical efficiency with altitude increases the best economy from 0.50 pound per B. H. P. at ground to 0.61 pounds (or more) at 30,000 feet. At ground the maximum economy is obtained at 1,500 r. p. m., possibly shifting to 1,700 r. p. m. at 30,000 feet. Also the change of mechanical efficiency at high levels, with change of speed, alters the fuel consumption per brake horsepower, so that at 30,000 feet 0.65 pound is required at 1,300 r. p. m., dropping to 0.61 at 1,700, and again increasing to 0.69 at 2,100 r. p. m. (The values are perhaps in error for 1,500 and 1,700 r. p. m., being, respectively, too high and too low, at altitudes of 25,000 and 30,000 feet). On the ground similar speeds change the consumption from 0.515 to 0.50 to 0.525. This is a 5 per cent variation from the optimum at ground, compared with a 13 per cent variation (−) at 30,000 feet. The fuel consumption per I. H. P. per hour, for a given speed, remains about constant at around 0.46 up to 10,000 or 15,000 feet; above this it increases with altitude. At ground, 1,500 r. p. m. seems the most economical speed, with a maximum variation of about 3 per cent for the changes of speed shown. At 30,000 feet, 1,700 r. p. m. appears to be



Plot No. 18.

the most economical speed, with about 4 per cent variation. The fuel consumption data will be considered later, utilizing the B. t. u. supplied as a means of attack, instead of the pounds per horsepower hour.

The tabulated values of I. H. P. and B. H. P. were also plotted on plot 16 in the same manner as the other values shown on plots 16 and 17. Deduction can be made more rapidly if the horsepowers are plotted, one curve for each altitude with r. p. m. as abscissæ and horsepower as ordinates, as on plots 18, 19, and 20.

III. RELATIONS BETWEEN POWER AND SPEED.

Plot 18 is interesting as showing how the relations between power, speed, and relative density of the air (altitude) form a warped surface when plotted on three dimensions. The B. H. P. would be zero when the relative density of the air became about 0.1 of the density at the ground. Also, no power can be secured from the engine, with open throttle, when it is loaded until the speed drops to about 450 r. p. m. For a given density the relation between speed and power is the intersection of a plane through the relative density coordinates and the warped surface. Such curves are shown more accurately on plot 19, in the customary manner of presenting engine characteristics. The extensions of the B. H. P. curves to speeds much below 1,200 r. p. m. are, to a large extent, speculation, hence the extensions are shown in dashes. At ground level a fairly large increase in brake power comes from increasing the speed from 1,300 to 2,100 r. p. m. The gain is less and less as the altitude increases, until at 30,000 feet practically no gain in power results when the speed is increased above 1,700 r. p. m. The total gain from 1,300 to 2,100 r. p. m. at 30,000 feet is about 40 per cent, 33 per cent gain being made from 1,300 to 1,700. On the ground, the per cent increase of power is the same (33 per cent) between 1,300 and 1,700 r. p. m., while the total gain from 1,300 to 2,100 is about 50 per cent.

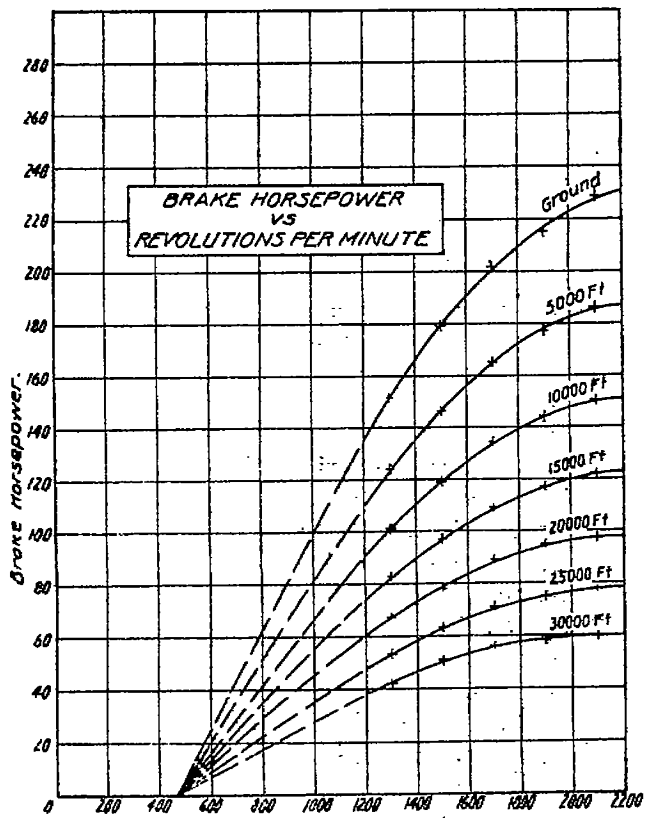
The curves of I. H. P. versus speed, for several altitudes, plot 20, differ from the B. H. P. curves by the addition of a variable friction loss to the B. H. P. curves.

The I. H. P. curves apparently would converge, and at about 450–500 r. p. m. the engine would "stall" at open throttle, because no power would be available above that required to overcome the friction of about 10 horsepower at this speed. In the actual engine it is probable that carburation would go bad before this point was reached.

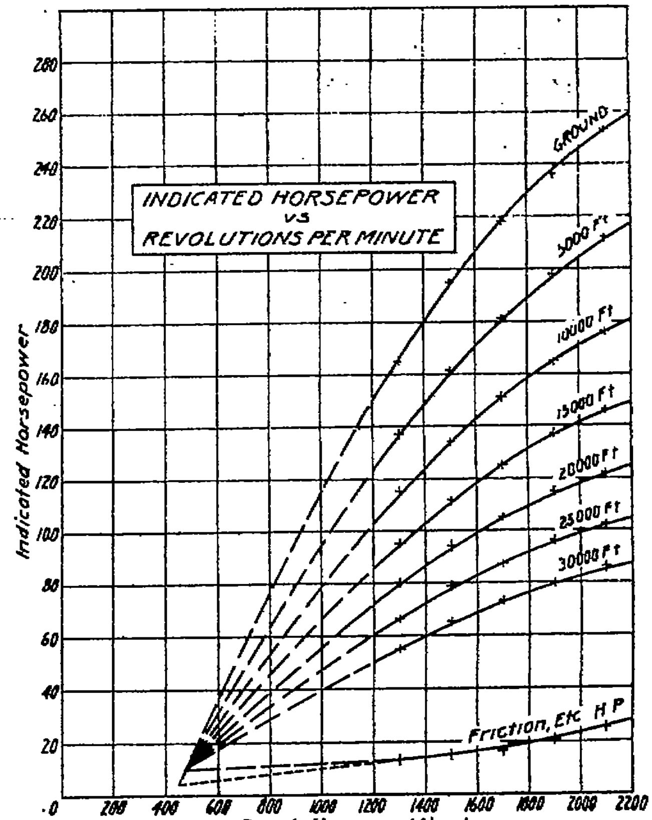
IV. FRICTION LOSSES.

On plot 20 is also shown the friction horsepower, a constant for each speed, which was added to the original B. H. P. altitude curve for each speed in order to obtain the I. H. P. The plotted value at 1,700 r. p. m. falls below the curve as drawn, and if the curve were drawn through it, the shape would be distinctly changed. The friction horsepower at speeds below 1,300 r. p. m. was speculated upon, in the absence of data. On plot 21, speed is used as abscissæ, but the ordinates are proportional to the "indicated" torque. A constant times the numerical scaling used will give true indicated torque as the scaling numbers are the I. H. P. times 100 divided by r. p. m. The same scaling is used for friction torque. The dash curve, which is the most logical extention of the friction horsepower curve on plot 20, indicated a decrease of friction torque with increase of speed, from 500 to 1,500 or 1,700 r. p. m., increasing again for higher speeds. The dotted curve is frankly a constant friction torque line from lowest speeds to about 1,500 r. p. m. It is reproduced on plot 20 in dots. The dash curve (reverse curve on torque) is more nearly the truth as shown by these tests.

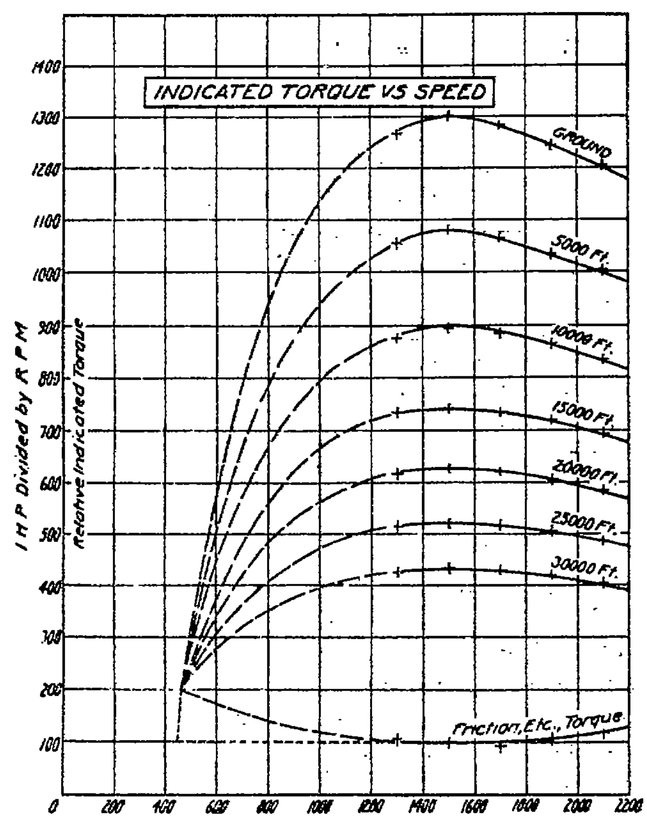
A plain bearing, with constant load, and using an oil of constant viscosity, will show friction torque increasing with increase of speed. Increase of speed, however, decreases the viscosity of the oil due to heating by the increased total friction. In the engine the heating is considerably greater than in a plain bearing because of the greater heat from the burning of more fuel at greater speeds. This increase of temperature will reduce the viscosity of the oil and this reduction of viscosity will reduce the friction, and may be sufficient to reduce the total friction torque. The pumping loss (lower loop of indicator card) would be nearly constant with open throttle, even over a considerable range of low speeds. The power required to over-



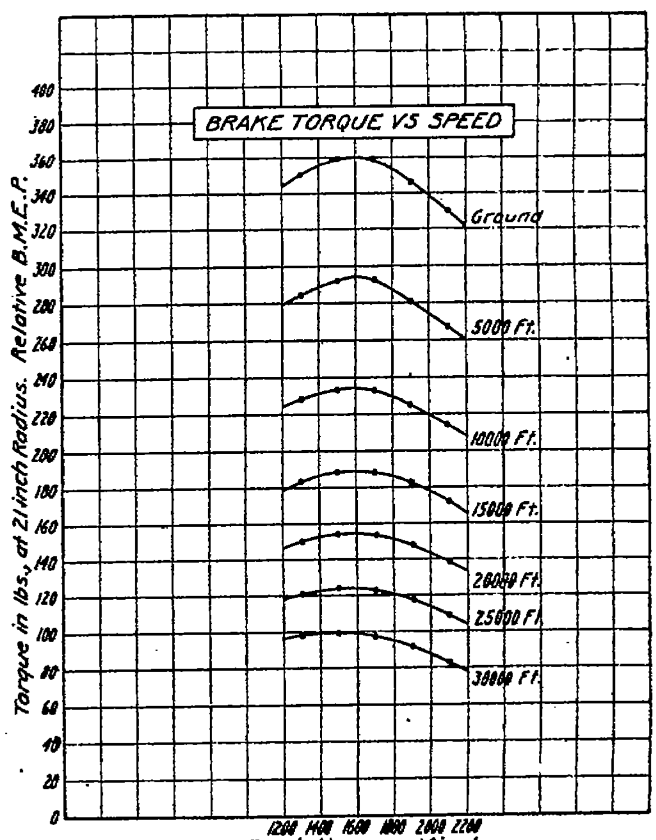
Plot No 19



Plot No. 20.



Plot No.21



Plot No.24

come the friction of the bearings and to drive the gears, magnetos, pumps, etc., would not change much at low speeds. Altogether it is suggested that the friction power loss can be expressed by a formula of the type

$$F=a+bN+cN^2+dN^3,$$

in which

F=friction losses.

N=r. p. m.

a, b, c, and d, = coefficients (not necessarily constants) which include variables depending upon bearing pressures (gas and inertia), piston rubbing, pump and magneto driving power, temperature, oil characteristics, etc.

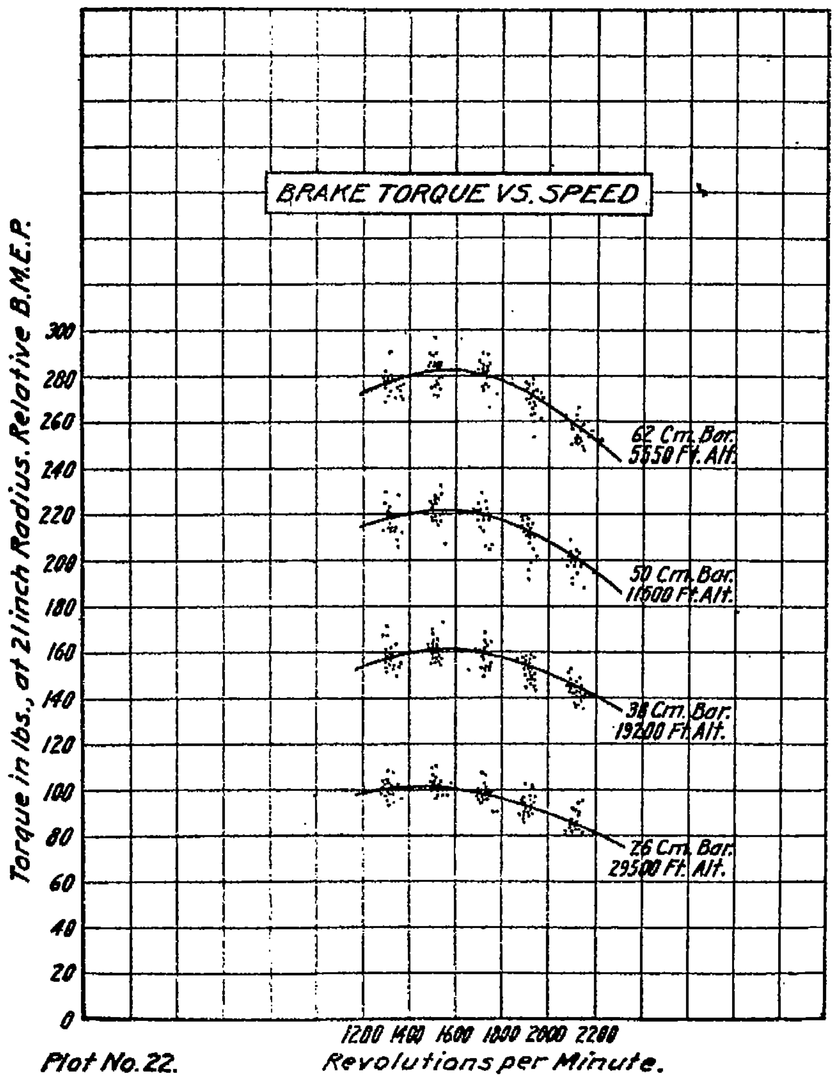
At higher speeds, the friction losses would increase much more rapidly than at low speeds.

It may seem that too much attention is being paid to this matter of friction losses. The reason for endeavoring to discover the fundamental laws controlling the mechanical and other losses is that the effect of these losses is much magnified at high altitudes. The mechanical efficiency of the engine is a dominant factor in the performance of a plane at high altitudes. A knowledge of the amount of the items of mechanical losses is therefore a necessary prelude to improvements in design, as well as for use in obtaining information concerning the heat distribution, the fuel consumption, etc. For these reasons, and in lieu of more definite data, several indirect methods have been used in the attempt to deduce the truth.

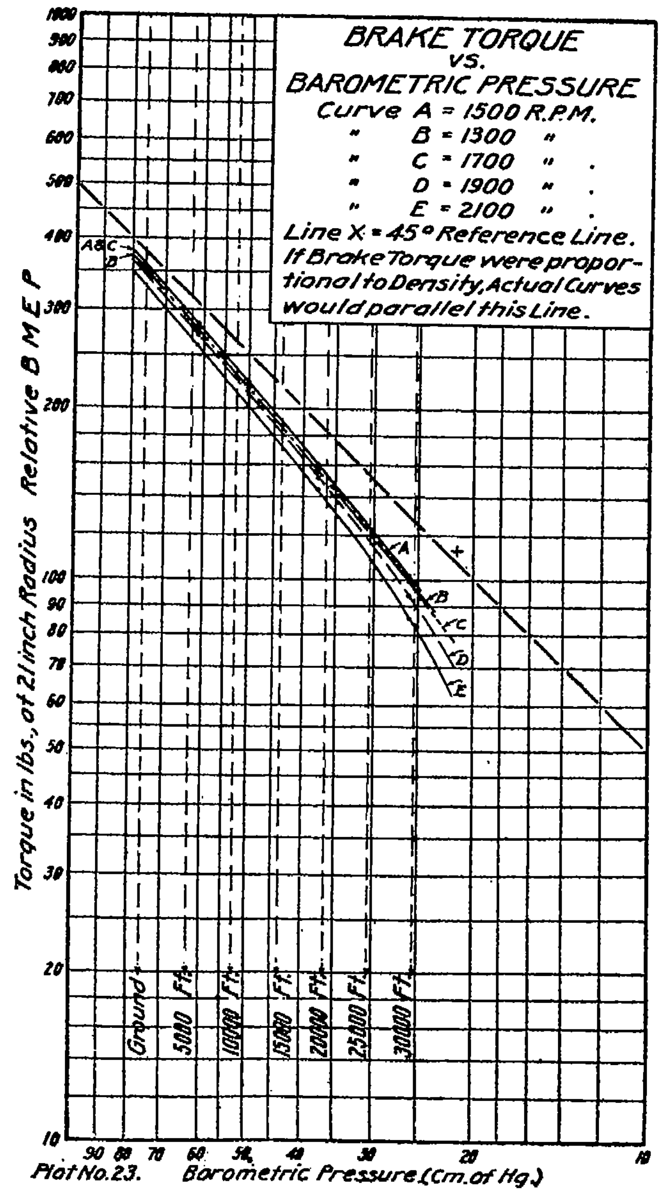
Some attempts have been made to measure the losses of internal combustion engines by measuring the power required to drive them at several speeds. Another suggestion is to cut off the ignition from each cylinder, in turn, and to note the power loss when speed is maintained. Perhaps it would be well to repeat these latter tests with two or more cylinders cut out at one time. The errors in measuring friction by these methods need not be discussed here. By taking the values of friction resulting from such tests, and from such assumptions as are here made, it would seem possible to know the absolute accuracy of each method of assumption. A suitable indicator is, of course, the logical solution of the problem.

The friction horsepower of the Hispano-Suiza engine is shown to a more open scale on plot 25, using the same values as on plot 20, and also all values shown in Table 1. It seems to increase very slowly from 1,300 to 1,700 r. p. m. and then to rise very rapidly. There is reproduced, also on plot 25, a curve given in Automotive Industries, January 23, 1919, page 212, for a class B war-truck engine. The method of obtaining the data for this latter curve was not stated, and is not known, but it probably was obtained by measuring the power required to run the engine at various speeds, while still hot from previous operation at open throttle. These two curves have been changed to friction torque (friction mean effective pressure) by the device of dividing F. H. P. by r. p. m., and thus shown on plot 26. The scaling is not the numerical value of torque or M. E. P. The numerical values of F. M. E. P. are given in Table 33. The curves for both Hispano-Suiza and class B truck engines have the same general characteristics, showing friction torque to decrease at first with increase of speed from the lower speeds, reaching a minimum value at some intermediate speed (dependent, probably, upon the engine design), and then increasing according to some function of the speed, which function may be approximated by raising the speed to an exponent greater than unity. On plot 27 the curves of plot 25 are reproduced, plotting the logarithms of r. p. m. against the logarithms of F. H. P. The two curves are seen to be of the same type (form of equation) but with different engine constants. With the lower speeds the friction horsepower apparently increases with r. p. m raised to the 0.78 power, that is, F. H. P. increasing less rapidly than the r. p. m. After a short transition period the F. H. P. seems to increase as the r. p. m raised to the 2.28 power—not quite the cube of speed. It should be noted that there are separate numerical scalings for the two engines.

The matter of friction losses was considered in a paper "High Speed Internal Combustion Engines," by Mr. H. R. Ricardo, appearing in Engineering (London), May 24, 1918, page 588. Some of the numerical estimates from this paper are abstracted in Table 4. The bearings and accessories take about 1.8 pounds per square inch pressure upon the piston (of the mean effective pressure), the piston friction about 7.2 pounds per square inch and the fluid pumping loss (lower loop of diagram M. E. P.) about 3.4 pounds per square inch. As a check on the accuracy



Plot No. 22.



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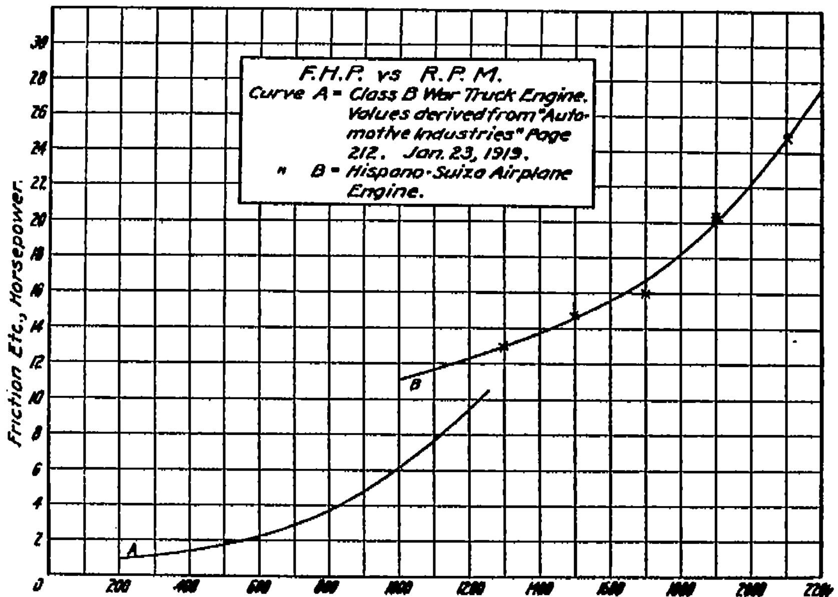
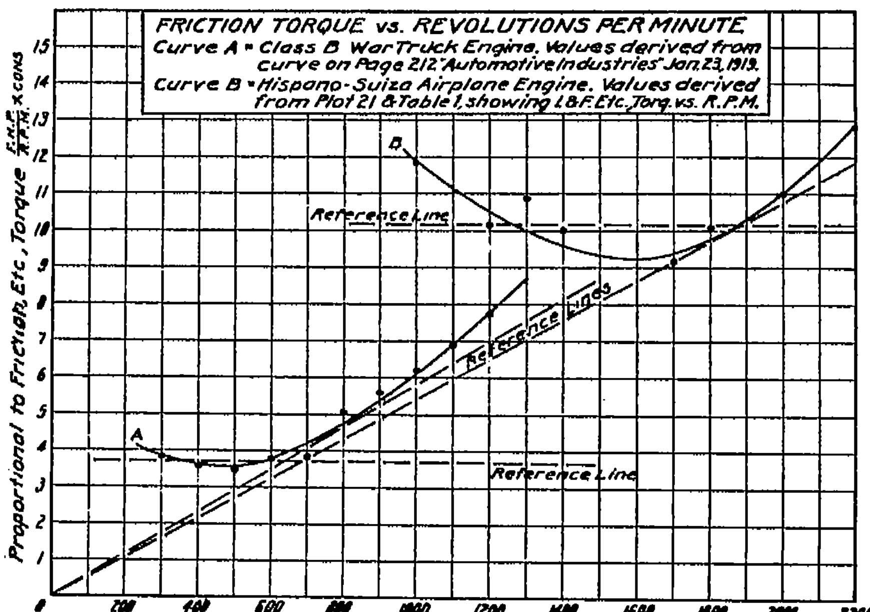
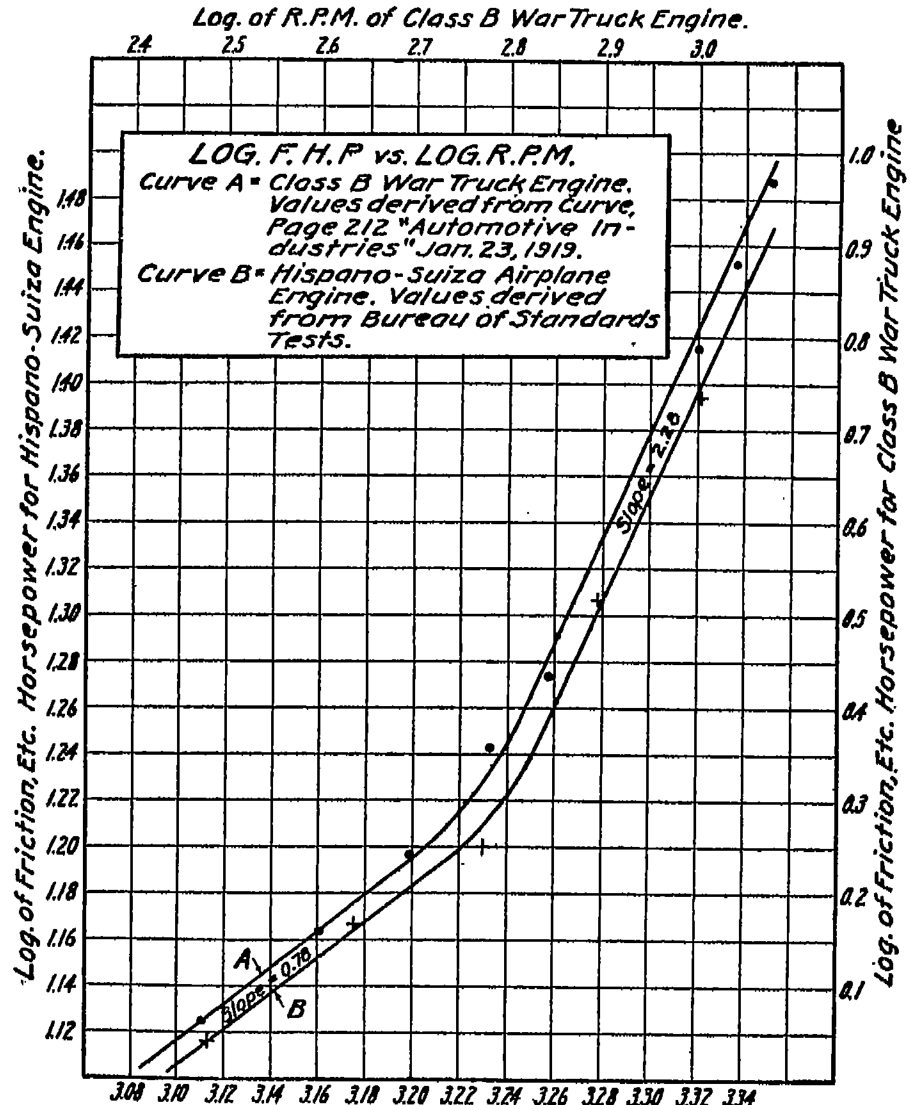


Plot No. 25.



Plot No. 26.



Plot 27.

of these values, some data on the power required to drive the water pumps of the 200-horsepower Austro-Daimler aero engine were found in Engineering (London) of November 8, 1918, page 537. By extending the curve through the values there given, according to the law that the pump power varies with the cube of speed, it was found that the pump would require from 0.14 to 0.41 pound per square inch piston pressure at normal engine speeds. This checks Mr. Ricardo's values of 0.3 to 0.5 pound per square inch. It also demonstrates that something besides the water pumps causes the F. H. P. to rise nearly with the cube of the r. p. m. at higher engine speeds. It probably means that inertia forces at high speeds cause metal-to-metal contact between piston and cylinder. Inertia forces increase with the square of the speed. Therefore the power required to overcome friction from inertia forces will tend to increase with the cube of the speed, and it may be concluded that speed is more of a factor than mean effective pressure in determining friction of the piston.

The subject of piston friction deserves special study. If it is possible to relieve the pistons in internal-combustion engines of their function as a crosshead, it may be possible greatly to increase the mechanical efficiency of the engine. Taking the friction losses in Table 4 (Ricardo's values), and eliminating the pumping losses, the bearing, etc., losses become about 20 per cent of the total, and the piston friction about 80 per cent of the mechanical losses of the engine.

Working upon the idea that the brake torque might shed some light upon the validity of the assumption that the friction horsepower was dependent upon speed and independent of altitude, and in order to furnish a check on the original B. H. P. and I. H. P. curves for each speed group, the original data from tests are plotted on plot 22, "pounds pull on the brake arm" versus r. p. m. This pull on brake arm is numerically equal to the brake torque, times a constant, and also to the brake M. E. P., times a constant. Curves were drawn through the mean of the points for each test altitude. Then, for speeds of 1,300, 1,500, 1,700, 1,900, and 2,100 r. p. m., the brake torque was read from these curves, and plotted on logarithmic cross-section paper, plot 23, with brake torque versus barometric pressure, using a separate curve for each speed. At 1,500 r. p. m., the brake torque is at its maximum for all altitudes, apparently being a straight line up to about 20,000 feet, with a slope of about 1.17 for its straight portion. This means that the brake torque and B. M. E. P. are equal to a constant times the density of the atmosphere raised to (about) the 1.2 power, and is not directly proportional to the density. The brake torque at 1,700 r. p. m. is the same as at 1,500 from ground up to 20,000 feet, falling off from proportionality at higher altitudes. For 1,300 r. p. m. the brake torque is slightly less than at 1,500 or 1,700 on the ground, but maintains, best of all, the relation

$$\text{B. m. e. p.} = \text{cons.} \times (\text{density of atmosphere})^{1.2}$$

even up to 30,000 feet. At this altitude 1,300 r. p. m. gives greater torque than 1,700 r. p. m. and nearly equal to 1,500 r. p. m. The 1,900 r. p. m. torque is nearly as great as the torque of 1,300 r. p. m. when on the ground, but at 15,000 feet it begins to fall away from the $(\text{density})^{1.2}$ relation. The brake torque at 2,100 r. p. m. perhaps starts out by varying with $(\text{density})^{1.2}$, but follows it only to about 12,000 feet, when it decreases more and more rapidly as the density is decreased.

From fundamental facts, the indicated mean effective pressure upon the piston must be almost proportional to the density of the air except for changes in the carburetion. The indicated mean effective pressure, minus the mean effective pressure required to overcome the friction losses, gives the brake mean effective pressure. Plot 23 seems to show the brake mean effective pressure, for a given constant speed, to be a combination of straight line at relatively high densities of air with a curve dropping downward for the lower densities. Perhaps the straight line is, in truth, not straight, but a curve, so slight as to appear straight within the accuracy of the cross-section paper and data as used here. If these are really curves, then it is incorrect to assume that the brake mean effective pressure varies with the density of the atmosphere raised to a certain power. If it is a curved line, then the relation may be an equation of the form

$$\text{I. M. E. P.} - \text{F. M. E. P.} = \text{B. M. E. P.}$$

in which F. M. E. P. may be a constant for any given speed.

It is the belief of the writer, based on the fundamental laws and on the data here presented, that this latter form is very close to the truth, i. e., that the friction mean effective pressure is practically a constant for a given speed and independent of the altitude. Plots 22, 23, and 24 are comparable with the log curves of power versus barometer for the several speed groups. But the B. H. P. of plots 1, 4, 7, 10, and 13 are replaced by brake torque in plot 22. As this is a slightly different method of attack and is carried out independently, it tends to confirm the belief in the correctness of the original assumption.

In order to present these results in the usual form, the characteristic curves of torque versus speed for different altitudes are given on plot 24. Again this shows the maximum torque on the ground and up to 10,000 feet altitude to be at about 1,600 r. p. m. occurring at slightly lower speeds as the altitude increases (around 1,500 r. p. m. at 30,000 feet). The actual loss of brake torque (B. M. E. P.) on the ground, due to increasing the speed from 1,800 to 2,100 r. p. m., is twice that when at 30,000 feet altitude. On a percentage basis, the loss at ground for this speed change is about 6 per cent. The loss at 30,000 feet is about 10 per cent. Using values of indicated torque (I. M. E. P.) read from the curves of plot 21, a loss of about 5 per cent of the indicated torque at 1,800 r. p. m. results from increasing the speed to 2,100, both on the ground and at 30,000 feet altitude. Perhaps it is a little more at 30,000 feet than at the ground.

V. GAIN OF POWER THROUGH INCREASE OF SPEED.

The change of power due to a change of speed, at different altitudes, is a subject that has been previously noted several times. These relations will now be taken up again in connection with Table 5 and plots 28 and 29.

Taking the I. H. P. and B. H. P. values in Table 1, the gain of power was tablulated in Table 5 for an increase of 200 r. p. m. from 1,300 to 1,500, from 1,500 to 1,700, etc., at each of the altitudes previously used. These gains of power are also shown as percentages of the power at the lower of the two speeds.

It also seemed desirable to collect all of the original constant speed curves showing the relation of horsepower and altitude (Table 1 and plots 1, 4, 7, 10, and 13) onto one sheet, and to present them on ordinary instead of logarithmic scaling. This is done on plot 28, the ordinates of which are I. H. P. and B. H. P., distances upon which are directly proportional to horsepower (arithmetic scaling). By using relative density of the atmosphere an abscissae (density at ground equals unity) the I. H. P. relations become straight lines passing through zero power at zero density. The B. H. P. relations are nearly straight lines, curving slightly, and apparently showing no power delivered when the density of atmosphere becomes about one-tenth of that at the ground. It may be remarked that the curvature of these B. H. P. versus density curves is exaggerated (to the eye) when plotted upon logarithmic cross-section paper (compare with plots 1, 4, 7, 10, and 13). The curvature upon plot 28 is hardly noticeable.

A scale of altitudes in feet is superposed upon the relative density scale. Altitudes of 5,000, 10,000, 15,000, 20,000, 25,000, and 30,000 feet are also shown as abscissae. They are logarithmically spaced, such spacing being due to the relation between barometric pressure and altitude.

The temperature of the atmosphere for these tests was nearly constant. In actual flight the temperature changes with the altitude. A change of temperature not only affects the density of the air, but it may also affect carburetion. In so far as it alters the density it is equivalent to a change of altitude. By the use of density instead of altitude in plotting curves of engine performance, the temperature effects are accounted for except as they change engine performance through carburetion or engine cooling.

The curves of plot 28 show graphically the fact that an increase of 200 r. p. m. means a much greater gain of power at the lower speeds than at the higher, for any altitude. They also show that as the altitude increases a smaller power gain is secured for the same speed change. These gains are tabulated in Table 5, and plotted as curves (or straight lines) on plot 29. Using percentages instead of horsepower, plot 30 shows graphically the values of Table 5. At 30,000 feet it is noted that a gain of 2 B. H. P. made on increasing speed from 1,700 to 1,900 r. p. m.,

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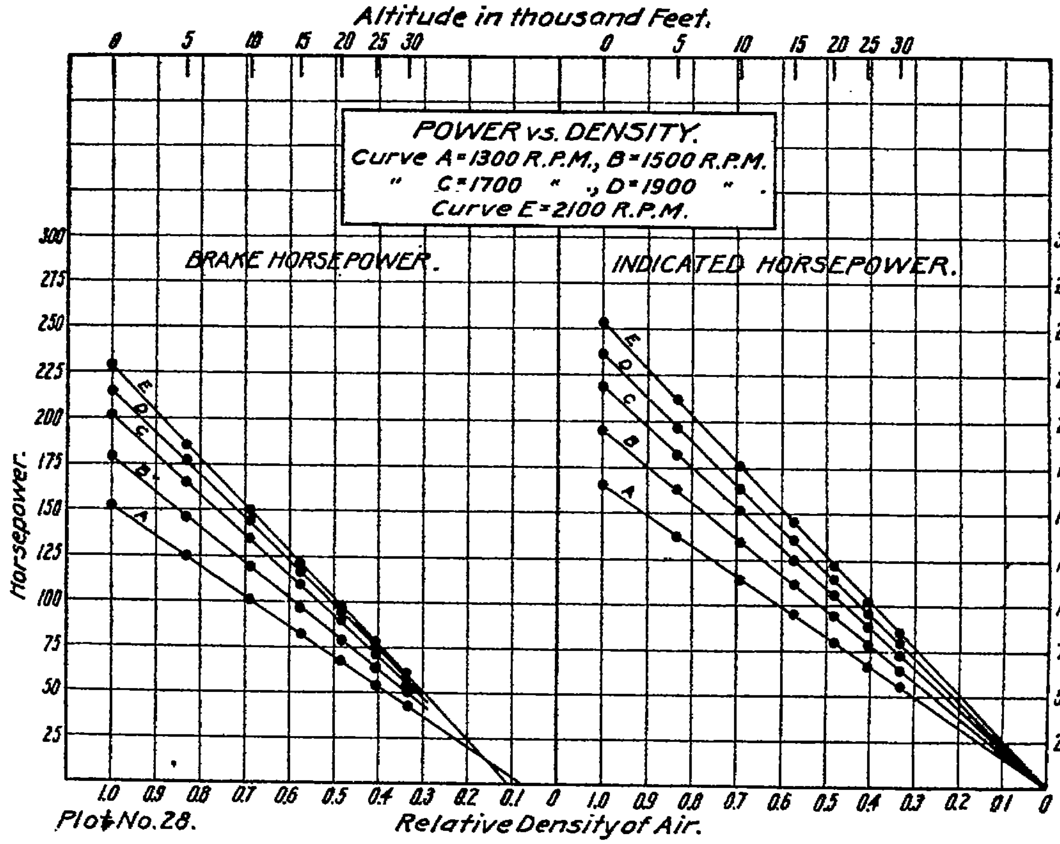
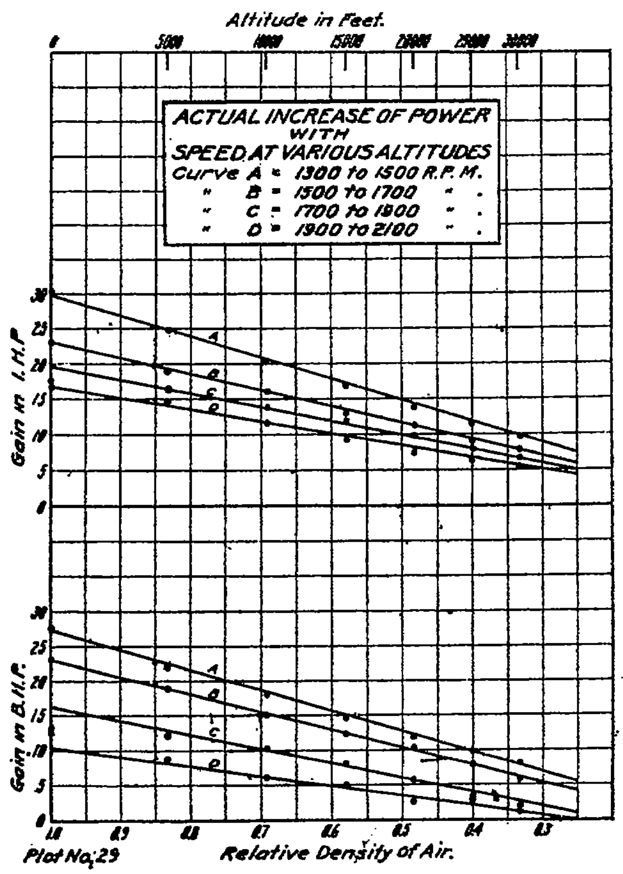


Plot No. 28.



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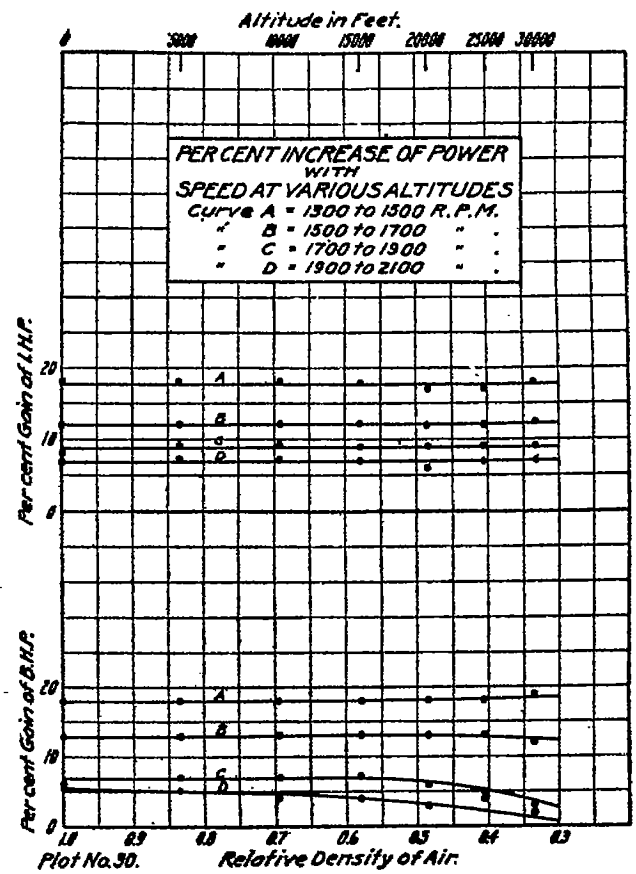

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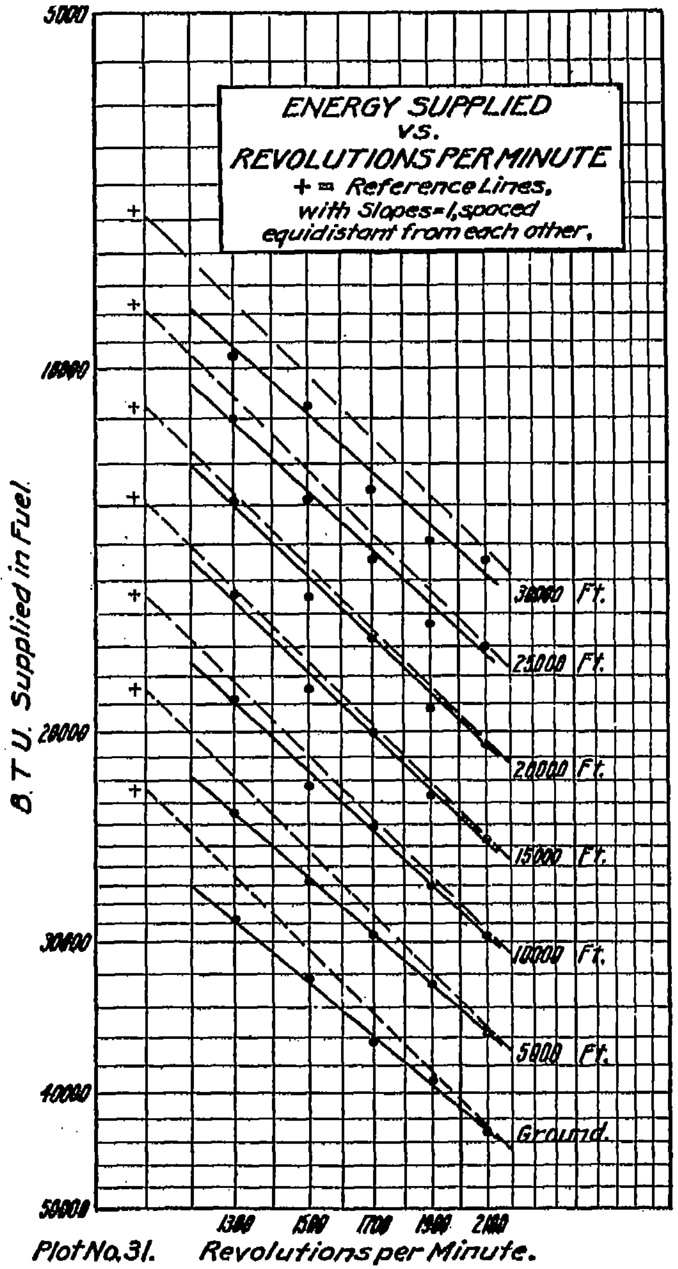
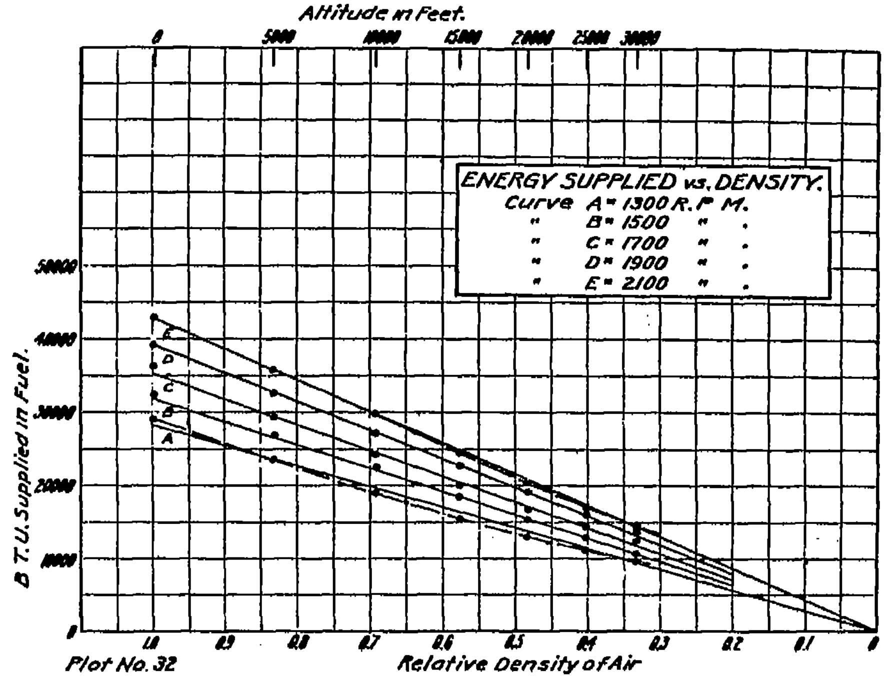
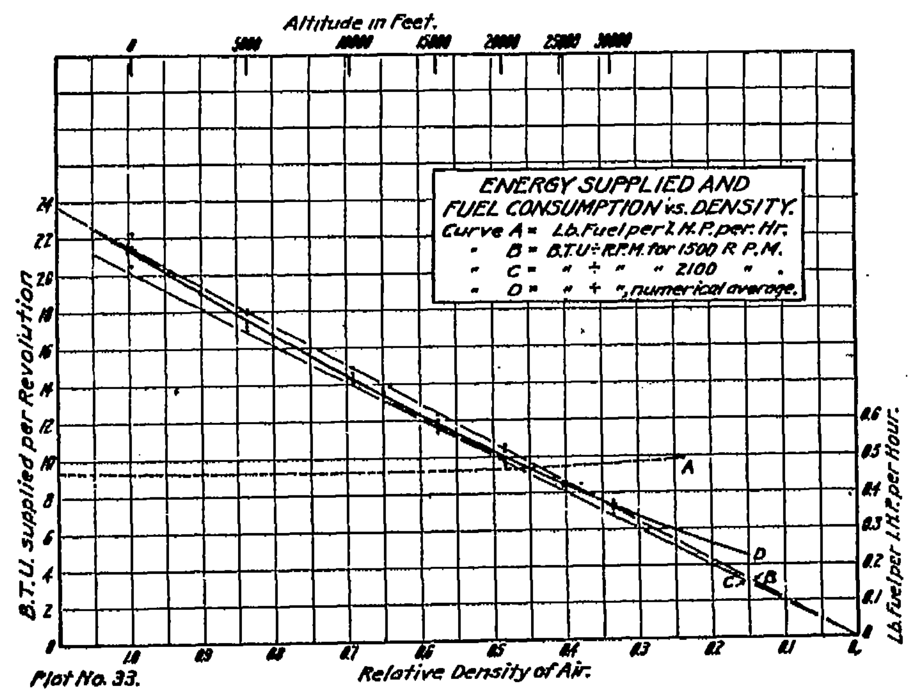


Plot No. 31.



Plot No. 32



Plot No. 33.

and 1 B. H. P. from 1,900 to 2,100. It has been noted that between 1,500 and 1,700 r. p. m. the engine is most efficient. At the higher altitudes the gains are relatively very small for an increase of speed above 1,700 r. p. m. The percentage increase of B. H. P. for an increase of speed from 1,700 to 1,900 or from 1,900 to 2,100 r. p. m. is smaller and smaller as the altitude increases, showing the effect of the constant friction torque at a given speed upon the power output, as the weight of charge decreases with the density of the atmosphere combined with he more rapid increase of friction torque due to increase of speed at higher speeds (plot 26). From 1,300 to 1,700 the friction torque apparently decreases with increase of speed. This is the reason why the per cent increase of B. H. P. due to increasing the speed from 1,300 to 1,500, and from 1,500 to 1,700 r. p. m. is nearly constant, as is indicated in Table 5. Altitude does not change the per cent increase of *indicated* horsepower when speed is raised from one definite rate to another.

VI. EFFECTS OF CHANGE OF DENSITY AND SPEED ON CARBURETION.

In studying the distribution of the energy supplied to the engine, the heat accounted for in the various ways, including I. H. P. and friction, seems to follow rather simple relations until the density of the atmosphere is greatly reduced. Then the relations apparently change to some other less simple law. This may be due to an incomplete application and understanding of the fundamental laws, or it may be due to difficulties of carburetion. In an endeavor to obtain more information on this subject, the heat supplied in the fuel per unit time (this is directly proportional to the weight of fuel supplied) was plotted against speed, using the logarithmically spaced coordinates on plot 31. The values were obtained from Table 2. The engine was operated with open throttle at all times. The carburetor was adjusted to give the best mixture for each change of conditions. Preliminary tests had been made to determine the best ignition timing, in which it was found that on the whole a fixed spark advance of about 23 degrees gave the best operating conditions at all speeds and altitudes, and that slight changes hardly affected the results. The spark timing was therefore the same for all the tests here considered.

The heat supplied per unit time was plotted on plot 32 against relative density of the atmosphere. This plot is the assembly of the "B. t. u. supplied" curves from plots 3, 6, 9, 12, and 15. The straight lines on plot 32 are frankly drawn through the zero-zero and then swung through this point so as to fit the other points as well as possible. The dash curves through 1,300 and 2,100 r. p. m. really fit the data better. The deviation is of the order of about 10 per cent of the gasoline supplied, which would allow for a change of mixture between, say, 14 and 15.5 parts of air to 1 of gasoline (weight proportions).

The heat supplied per unit time (from Table 2) was divided by the revolutions per minute, and is recorded on Table 6. These values are equal to a constant times the weight of gasoline supplied per suction stroke. These values show the effect of volumetric efficiency in decrease of charge with increase of speed at any given altitude. The values of the quotients of B. t. u. by r. p. m. are shown on plot 33. Straight lines were drawn through the points of zero density-zero gasoline and then forced to fit the points for 1,500 and for 2,100 r. p. m. The heavy curve, shown in dashes, is drawn through the numerical average of the points at each altitude. This plot shows, more plainly, the same facts as plots 31 and 32. Another method of attacking this problem is by means of the fuel consumption per indicated horsepower per hour, which will eliminate the variable efficiencies, both volumetric and mechanical. Fuel consumption curves are given on plots 2, 5, 8, 11, and 14, and sometimes indicate the maximum economy at moderate altitudes. As a rough check, the average weight of fuel per indicated horsepower at each altitude, as computed from Table 1, is given in Table 6, and is plotted on plot 33.

The deductions to be drawn from plots 31, 32, and 33 are as follows:

Assuming 100 per cent volumetric efficiency, the weight and the volume of air drawn into the cylinders should be directly proportional to the speed of the engine. Also assuming a constant weight proportion of gasoline to air for all speeds, the values on plot 31 should fall on 45° lines. They do not, but they show a maximum of 10 per cent more gasoline needed at 1,300 than at 2,100 r. p. m. The change of volumetric efficiency can account for this, because of the reduction of weight of air drawn in on each suction stroke at the greater speeds. Valve timing (inlet opening 10° late and closing 50° late) and temperature effects may be other contributing factors.

If the weight proportion of gasoline to air were constant at the several altitudes, then the distances between the plotted curves on plot 31 should be equal. This follows from the relation between density and altitude that the log of density equals a constant minus another constant times altitude. Hence equal increments of altitude will cause equal increments of log density. The plotted curves of values are not equally spaced for equal increments of altitude. As the carburetor was adjusted by hand for each test, the points indicate that the proper proportions of gasoline to air are not a constant when altitude is changed at constant speed. The 45° reference lines on plot 31 are arbitrarily drawn to pass through the test points of 2,100 r. p. m., and to be equally spaced, the spacing being the distance between the 2,100 r. p. m. points at the lower altitudes. This spacing is too great for the results shown at the higher altitudes. It has been noted that the appearance of curves on logarithmic cross-section paper are sometimes deceptive, and, for this reason, plot 33 is much better for this side of the problem. Evidently the engineers making the tests found that the leanest mixture could be used at around 15,000 feet, and greater weight proportions of gasoline to air were necessary at the other altitudes. Again, this change is of an order of magnitude, generally much less than 10 per cent. Too much reliance should not be placed upon the indications or tendencies shown on this plot and the two preceding ones. The remarkable features are the consistency with which the carburetor was adjusted at the beginning of each test. It is probable that the peculiarities of heat distribution at high altitudes are not entirely due to carburetion.

TABLE 1.—*Averaged test data and results.*

Speed (R.P.M.)	Altitude. Ground.	5,000 feet.	10,000 feet.	15,000 feet.	20,000 feet.	25,000 feet.	30,000 feet.	Computed.
BRAKE HORSEPOWER (from curves). [From plots 1 to 15, inclusive, 22 and 23.]								
1,500	179	146	119	96.7	78.6	68.5	50.2	....
1,700	202	165	134	109	89	71.6	56.2	....
1,900	215	177	144	117	94.6	75	58.2	....
2,000	228	185.5	150	122	97	78	59.3	....
"INDICATED" HORSEPOWER (from curves).								
1,300	164.5	137	114	95.2	80	66.7	55.2	....
1,500	195	162	134.5	112	93.8	78.3	65	....
1,700	218	181	150.5	125	105	87.6	73	....
1,900	236	197.3	164.3	136.3	114.8	95.6	79.7	....
2,100	253	212	176	146	122	102	85.2	....
FRICTION, ETC., HORSEPOWER (for altitudes, by difference).								
1,300	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
1,500	16	16	15.5	15.8	15.2	14.8	14.7	14.7
1,700	16	16	16.5	16	16	16	15.7	16
1,900	21	20.3	20.3	19.8	20.2	20.6	21.5	20.8
2,100	25	26.5	26	24	25	24	25.9	24.8
MECHANICAL EFFICIENCY (B.H.P.÷I.H.P.).								
1,300	92	90.4	88.5	86.3	83.6	80.2	74.4	....
1,500	91.8	90.1	88.6	86.3	83.8	81	77.3	....
1,700	92.6	91.2	89.1	87.2	84.8	81.7	77.1	....
1,900	91	89.7	87.6	85.6	82.4	78.4	73	....
2,100	90	88	85.8	83.2	80	75	70.5	....
BRAKE TORQUE (relative B.M.E.P.) (from curves). (Pounds pull at 21 inch radius.)								
1,300	350	284	228	183	150	121	98	....
1,500	359	292	233	188	154	124	99	....
1,700	359	292	233	188	153	123	97	....
1,900	345	280	225	183	148	118	92	....
2,100	330	267	215	172	139	109	83	....
INDICATED TORQUE×CONSTANT (relative I.M.E.P.) (I.H.P.÷R.P.M.).								
1,300	1,265	1,054	876	732	615	513	424	....
1,500	1,300	1,080	896	746	626	522	434	....
1,700	1,282	1,064	886	735	618	515	430	....
1,900	1,242	1,038	865	720	604	503	420	....
2,100	1,205	1,010	838	695	581	486	406	....
FRICTION, ETC., TORQUE×CONSTANT (relative F.M.E.P.) (friction, etc., H.P.÷R.P.M.)								
1,300	....	....	....	....	....	....	....	107
1,500	....	....	....	....	....	....	....	98
1,700	....	....	....	....	....	....	....	94
1,900	....	....	....	....	....	....	....	107
2,100	....	....	....	....	....	....	....	118
FUEL CONSUMPTION (Lbs. per B.H.P. per hour) (from curves).								
1,300	0.515	0.520	0.528	0.540	0.560	0.594	0.649	....
1,500	.500	.510	.520	.527	.546	.580	.635	....
1,700	.503	.510	.518	.529	.549	.572	.610	....
1,900	.512	.522	.534	.551	.575	.605	.650	....
2,100	.525	.535	.550	.572	.598	.635	.690	....
FUEL CONSUMPTION (Lbs. per I.H.P. per hour). (Computed from B. H. P. consumption and mechanical efficiency.)								
1,300	0.474	0.470	0.468	0.466	0.468	0.477	0.484	....
1,500	.459	.460	.461	455	.458	.470	.491	....
1,700	.466	.465	.461	.461	.465	.467	.470	....
1,900	.465	.468	.468	.471	.474	.474	.475	....
2,100	.473	.471	.472	.476	.479	.485	.487	....

TABLE 2.—*Averaged heat distribution, data and results.*

[From plots 1 to 15, inclusive.]

B. T. U. SUPPLIED IN FUEL, PER UNIT TIME (from curves).

Speed (R.P.M.)	Altitude.						
	Ground.	5,000 feet.	10,000 feet.	15,000 feet.	20,000 feet.	25,000 feet.	30,000 feet.
1,300	28,800	23,400	18,800	15,400	12,800	11,000	9,800
1,500	32,800	26,900	22,300	18,500	15,450	12,900	10,900
1,700	26,300	29,700	24,150	20,000	16,900	14,400	12,600
1,900	39,300	32,600	27,050	22,700	19,100	16,250	13,900
2,100	43,000	35,700	29,700	24,600	20,500	17,000	14,100

FRICTION, ETC., LOSSES, B. T. U. (computed).

1,300	595	590	580	570	580	585	645
1,500	690	620	660	670	670	650	650
1,700	705	695	720	605	695	700	727
1,900	920	880	880	850	870	900	935
2,100	1,160	1,142	1,130	1,130	1,165	1,105	1,095

EXHAUST LOSSES, B. T. U. (from curves).

1,300	12,600	10,300	8,350	6,750	5,530	4,540	3,650
1,500	15,000	12,200	9,850	7,950	6,500	5,300	4,300
1,700	17,750	14,400	12,550	9,400	7,640	6,230	5,050
1,900	19,300	15,700	12,700	10,300	8,450	6,850	5,600
2,100	20,800	17,140	14,010	11,240	9,020	7,060	5,470

JACKET LOSSES, B. T. U. (from curves).

1,300	5,000	4,660	4,330	4,020	3,750	3,490	3,230
1,500	5,950	5,400	4,900	4,400	4,000	3,600	3,250
1,700	6,400	5,870	5,350	4,920	4,560	4,250	4,000
1,900	6,400	5,950	5,550	5,150	4,830	4,420	4,200
2,100	7,740	6,730	5,940	5,160	4,610	4,250	4,030

B. T. U. IN B. H. P. (from curves).

1,300	6,850	5,550	4,470	3,600	2,940	2,365	1,865
1,500	7,700	6,320	5,200	4,230	3,470	2,790	2,220
1,700	8,770	7,170	5,850	4,740	3,880	3,110	2,450
1,900	9,400	7,670	6,230	5,050	4,100	3,250	2,530
2,100	10,320	8,360	6,680	5,290	4,145	3,285	2,620

B. T. U. IN I. H. P. (B. T. U. in B. H. P.÷mech. eff.÷100).

1,300	7,445	6,140	5,050	4,170	3,520	2,950	2,510
1,500	8,380	7,010	5,860	4,900	4,140	3,440	2,880
1,700	9,475	7,865	6,570	5,435	4,575	3,808	3,177
1,900	10,320	8,550	7,110	5,900	4,970	4,150	3,465
2,100	11,480	9,500	7,810	6,420	5,310	4,390	3,715

THERMAL EFFICIENCY ON I. H. P. (computed).

1,300	25.9	26.2	26.9	27.1	27.5	26.8	25.6
1,500	26.0	26.2	26.2	26.5	26.8	26.7	26.6
1,700	26.2	26.5	27.2	27.2	27.2	26.4	25.2
1,900	26.3	26.3	26.3	26.0	26.0	25.5	24.9
2,100	26.7	26.6	26.3	26.1	25.9	25.8	25.5

THERMAL EFFICIENCY ON B. H. P. (B. T. U. in B. H. P.×100÷B. T. U. supplied).

1,300	23.8	23.7	23.7	23.4	23.0	21.5	19.1
1,500	23.8	23.5	23.3	22.8	22.5	21.6	20.6
1,700	24.1	24.2	24.2	23.7	23.1	21.6	19.5
1,900	23.9	23.5	23.0	22.2	21.4	20.0	18.2
2,100	24.5	23.5	22.5	21.5	20.5	19.4	18.3

TABLE 2.—*Averaged heat distribution, data and results*—Continued.

FRICTION, ETC., LOSSES (per cent).

Speed (R. P. M.)	Altitude.						
	Ground.	5,000 feet.	10,000 feet.	15,000 feet.	20,000 feet.	25,000 feet.	30,000 feet.
1,300	2.1	2.5	3.1	3.7	4.5	5.3	6.6
1,500	2.1	2.7	2.9	3.6	4.3	5.1	6.0
1,700	1.9	2.8	3.0	3.5	4.2	4.9	5.8
1,900	2.4	2.8	3.3	3.8	4.6	5.5	6.7
2,100	2.7	3.2	3.8	4.6	5.2	6.5	7.6

EXHAUST LOSSES (per cent).

1,300	43.8	44.0	44.5	43.9	43.2	41.3	37.4
1,500	46.5	45.4	44.2	43.0	42.1	41.1	39.8
1,700	48.9	48.5	47.8	47.0	45.5	43.3	40.1
1,900	49.2	48.2	47.0	45.4	44.3	42.2	40.4
2,100	48.4	48.0	47.2	45.7	44.0	41.5	38.0

JACKET LOSSES (per cent).

1,300	17.4	19.9	23.0	26.1	29.3	31.8	33.0
1,500	18.4	20.0	22.0	23.8	25.9	27.9	30.1
1,700	17.6	19.8	22.2	24.6	27.2	29.5	31.7
1,900	16.3	18.3	20.5	22.7	25.3	27.6	30.2
2,100	18.0	19.0	20.0	21.0	22.5	25.0	28.0

PER CENT HEAT ACCOUNTED FOR (B. H. P.+frict.+exh.+jkt.).

1,300	87.1	90.1	94.3	97.1	100.0	99.9	96.1
1,500	90.8	91.6	92.4	93.2	94.8	95.7	96.5
1,700	92.5	94.8	97.2	98.8	99.9	99.3	97.0
1,900	91.8	92.8	93.8	94.1	95.6	95.3	95.5
2,100	93.6	93.7	93.5	92.8	92.2	92.4	91.9

TABLE 3.—*Friction, etc., horsepower and friction, etc., mean effective pressure (M. E. P. equals a constant times torque).*

[To accompany pls. 25, 26, and 27.]

3a. Class B war truck engine (computed from mechanical efficiency and I. H. P. curves, p. 212, Automotive Industries, Jan. 23, 1919).			3b. Hispano-Suiza airplane engine (computed from mechanical efficiency, etc., values given in Table 1 of this report).		
R. P. M.	F. H. P.	F.M.E.P. (pounds per square inch).	R. P. M.	F. H. P.	F.M.E.P. (pounds per square inch).
300	1.16	7.20	1,300	13.1	11.1
400	1.45	6.85	1,500	14.7	10.8
500	1.75	6.52	1,700	16.0	10.4
600	2.28	7.10	1,900	20.3	11.8
700	2.72	7.24	2,100	24.8	13.1
800	4.02	9.36			
900	5.03	10.40			
1,000	6.15	11.45			
1,100	7.60	12.86			
1,200	9.35	14.60			

TABLE 4.—*Friction losses.*

[Abstracted and computed from Engineering (London).]

[To accompany pls. 25, 26, and 27.]

"HIGH-SPEED INTERNAL COMBUSTION ENGINES," H. R. RICARDO, MAY 24, 1918, PAGE 588.

For petrol engines, losses are about:

1.—Bearings, etc	1.8	pounds per square inch of piston area.
2.—Piston friction	7.2	Do.
3.—Fluid pumping loss	3.4	Do.
Total	12.4	Do.
Brake M. E. P	118	Do.
Mechanical efficiency	90.6 per cent.	

1.—Losses due to bearings, auxiliaries, etc.:

(a) Bearings	0.75–1.00	pounds per square inch of piston area.
(b) Valve gear	.75– .80	Do.
(c) Magneto	.05– .10	Do.
(d) Oil pump	.15– .25	Do.
(e) Watpump	.30– .50	Do.
Total	2.00–2.65	

2.—Piston friction:

Largest single item; due to reciprocating motion, contaminated oil, etc.; extent proportional to thrust on walls, indirectly to rubbing velocity and area. Empirical formula for which is:

$$\text{Piston friction} = \frac{\dfrac{\text{Mean fluid pressure}}{4} + \dfrac{2 \times \text{mean inertia pressure}}{3}}{10} + \text{Constant.}$$

Constant varies from 1.5 to 4 pounds per square inch of piston area.

3.—Fluid pumping losses:

Range=2.3 pounds per square inch at 100 feet per second gas velocity; to 9.2 pounds per square inch at 24 feet per second. (About as cube of gas velocity or R. P. M.)

"THE 200-HORSEPOWER AUSTRO-DAIMLER AERO ENGINE," NOV. 8, 1918, PAGE 539.

Power required for water pump.

Pump R. P. M.	British gallons per minute, 2 lbs. per sq. in. head.	Horsepower delivered by pump.	Horsepower demand by pump, if efficiency=50 per cent.	Engine R. P. M.
1,000	12	0.0168	0.034	525
1,200	21	.0294	.060	633
1,400	30	.0419	.084	740
1,600	37	.0517	.103	845
1,800	43	.0601	.120	950

Extending curve on assumption that pump power varies with cube of speed.

Engine R. P. M.	Engine horsepower.	B.M.E.P.	Pump demand (2-pound delivery).		Pump demand (6-pound delivery).		Pump M. E. P.	
			Horsepower.	Per cent.	Horsepower.	Per cent.	2-pound delivery.	6-pound delivery.
1,200	186	123.5	0.210	0.113	0.48	0.137	0.139	0.164
1,400	200	123.3	.236	.118	.56	.28	.146	.345
1,500	212	122	.266	.125	.66	.313	.153	.38
1,600	222	119.7	.293	.132	.76	.343	.158	.41

TABLE 5.—*Gain of power through increase of speed.*

[To accompany Pls. 29 and 30.]

INCREASE OF B. H. P. (from values in table 1).

Change of R. P. M.		Altitude.						
From—	To—	Ground.	5,000 feet.	10,000 feet.	15,000 feet.	20,000 feet.	25,000 feet.	30,000 feet.
1,300	1,500	27.6	22.1	18.1	14.6	11.7	9.9	8.2
1,500	1,700	23	19	15	12.3	10.4	8.1	6.0
1,700	1,900	18	12	10	8	5.6	3.4	1.9
1,900	2,100	13	8.5	6	5	2.4	3	1.1

PER CENT INCREASE OF B. H. P. (H. P. at lower speed=100 per cent).

1,300	1,500	18	18	18	18	18	18	19
1,500	1,700	13	13	13	13	13	13	12
1,700	1,900	6	7	7	7	6	5	3
1,900	2,100	6	5	4	4	3	4	2

INCREASE OF I. H. P. (from values in table 1).

1,300	1,500	30.5	25	20.5	16.8	13.8	11.6	9.8
1,500	1,700	23	19	16	13	11.2	9.3	8
1,700	1,900	18	16.3	13.8	11.8	9.5	8	6.7
1,900	2,100	17	14.7	11.7	9.2	7.2	6.4	5.5

PER CENT INCREASE OF I. H. P. (H. P. at lower speed=100 per cent).

1,300	1,500	18	18	18	18	17	17	18
1,500	1,700	12	12	12	12	12	12	12
1,700	1,900	8	9	9	9	9	9	9
1,900	2,100	7	7	7	7	6	7	7

TABLE 6.—*Relative amounts of energy supplied per stroke.*

[To accompany pls. 31, 32, and 33.]

B. T. U. SUPPLIED IN FUEL PER UNIT TIME DIVIDED BY R. P. M. (values from table 2)

Speed (r. p. m.).	Altitude.						
	Ground.	5,000 feet.	10,000 feet.	15,000 feet.	20,000 feet.	25,000 feet.	30.000 feet.
1,300.....	22.14	18.00	14.46	11.85	9.85	8.46	7.53
1,500.....	21.50	17.95	14.86	12.33	10.30	8.60	7.20
1,700.....	21.35	17.45	14.20	11.76	9.88	8.47	7.41
1,900.....	21.4	17.15	14.23	11.95	10.55	8.56	7.32
2,100.....	20.48	17.00	14.14	11.71	9.76	8.10	6.86
Average.	21.4	17.5	14.4	11.9	10.1	8.4	7.3

FUEL CONSUMPTION, LBS. PER I. H. P. PER HOUR (averaged from table 1).

Average.	0.467	0.467	0.466	0.466	0.469	0.474	0.481

APPENDIX.

RESULTS OF THE TESTS USED AS A BASIS FOR THIS REPORT.

2,100 R. P. M.

Test No.	Barometer.	B. t. u. in exhaust.	B. t. u. in jacket.	B. t. u. in B. H. P.	B. t. u. supplied.	B. H. P.	Fuel consumption Lb./B. H. P./hr.
99-A....	62.0	14,980	6,690	7,650	32,900	177.6	0.536
B....	"	12,450	6,710	7,770	35,180	177.9	.552
	49.9	12,730	6,375	6,140	29,500	139.5	.599
C....	"	13,000	6,520	6,275	29,520	142.7	.573
D....	37.6	8,670	6,210	4,450	22,450	100.3	.629
	"	9,340	5,530	4,450	21,900	100.4	.600
E....	25.7	5,130	4,290	2,675	15,920	60.6	.742
F....	"	5,940	4,890	2,682	15,210	60.6	.692
100-A....	61.9	16,645	6,510	8,070	33,880	184.5	.525
B....	"	15,810	6,610	7,690	32,200	178.5	.519
	49.8	13,408	7,015	6,195	25,100	143.0	.502
C....	"	13,260	6,610	6,210	27,120	143.8	.542
D....	37.5	9,240	5,410	4,540	21,480	103.9	.587
	"	9,515	5,960	4,480	19,960	102.7	.553
E....	25.5	5,580	4,805	2,635	16,110	60.0	.759
	"	5,720	4,725	2,575	14,150	58.7	.681
101-A....	62.1	....	....	7,700	....	184.1	....
	"	16,550	7,700	7,600	33,650	179.5	.549
B....	"	14,480	5,410	7,200	35,780	176.8	.617
	"	18,750	6,960	7,920	35,200	184.0	.552
C....	"	17,450	6,930	7,760	32,700	180.0	.526
D....	44.9	12,840	4,730	5,820	26,140	133.2	.558
E....	"	12,620	3,685	6,050	25,180	137.9	.516
F....	37.8	9,340	4,895	4,300	20,980	97.4	.606
	"	8,910	4,300	4,250	17,740	95.6	.517
G....	"	9,510	4,000	4,270	19,520	97.1	.570
H....	26.0	6,570	4,960	2,630	14,180	59.5	.673
I....	"	8,470	5,910	2,590	13,130	58.9	.629
J....	"	6,220	5,240	2,545	13,900	58.0	.678
105-A....	62.1	16,360	5,760	7,770	30,040	177.8	.492
B....	25.8	7,445	5,165	2,800	12,405	63.8	.567
C....	25.9	6,719	5,378	2,817	13,095	64.2	.576
D....	"	6,579	4,928	2,738	13,040	62.4	.598
E....	37.7	9,720	6,135	4,489	18,830	102.8	.527
F....	"	10,030	6,135	4,462	18,710	102.3	.517
G....	"	10,170	6,428	4,515	17,810	102.5	.503
H....	50.2	15,870	9,140	6,100	24,510	139.0	.513
I....	"	13,099	6,538	6,150	26,260	140.5	.530
J....	"	14,500	5,760	6,199	26,120	140.9	.529
K....	62.3	....	....	7,774	35,310	177.7	.572
L....	"	15,805	7,208	8,005	34,940	183.0	.541
106-A....	62.1	16,930	6,330	7,850	33,540	177.6	.528
B....	"	....	....	....	31,410	164.8	.543
	49.8	13,560	5,684	5,915	27,070	135.0	.565
C....	"	13,610	5,854	5,935	28,500	135.1	.604
D....	37.6	9,800	5,140	4,370	20,880	99.5	.589
	"	....	....	....	....	97.6	....
E....	25.7	6,100	4,239	2,488	15,145	56.6	.752
F....	"	6,338	4,235	2,548	13,400	58.3	.662
	61.9	17,285	5,975	7,600	35,110	173.8	.593
110-A....	25.7	4,750	4,040	2,517	15,655	58.9	.771
B....	"	4,910	3,960	2,234	15,450	58.8	.847
C....	37.6	7,490	4,985	4,515	23,180	103.2	.635
	"	7,490	5,345	4,610	23,590	105.7	.632
D....	"	7,055	4,700	4,490	23,450	102.8	.658
E....	49.8	10,015	5,975	6,241	31,740	144.8	.627
F....	"	10,796	6,503	6,035	31,200	139.3	.650
G....	61.9	11,895	6,095	7,943	35,040	185.5	.544
H....	"	....	....	....	....	181.5	.569
I....	37.5	....	....	....	....	103.2	.599
	"	....	....	....	....	102.9	....
J....	"	....	....	....	....	101.8	.601
	"	....	....	....	....	101.8	.607
111-A....	25.7	6,200	4,330	2,920	14,400	67.1	.609
B....	"	6,090	4,185	2,990	14,300	68.3	.584
C....	37.6	8,930	5,235	4,395	20,420	100.4	.575
D....	"	8,925	5,535	4,650	21,350	106.2	.559
E....	"	9,015	5,170	4,535	24,580	103.8	.670
	49.95	11,508	5,680	6,320	28,300	144.5	.553
F....	"	11,400	5,660	6,330	28,000	145.9	.584
G....	61.9	14,650	6,080	7,880	34,020	180.8	.534
	"	14,760	6,150	8,180	35,930	187.8	.544
H....	"	14,180	5,780	8,190	34,020	188.7	.502
	"	14,215	5,850	8,130	34,650	185.5	.521

Results of the tests used as a basis for this report—Continued.

1,900 R. P. M.

Test No.	Barometer.	B. t. u. in exhaust.	B. t. u. in jacket.	B. t. u. in B. H. P.	B. t. u. supplied.	B. H. P.	Fuel consumption Lb./B. H. P./hr.
99-A....	62.0	14,700	6,085	7,380	32,000	172.0	0.541
B....	"	11,800	6,420	7,470	32,600	170.8	.533
	49.9	11,700	6,110	5,930	27,300	134.9	.574
C.....	"	11,770	5,985	6,040	26,620	137.3	.537
D....	37.6	8,310	5,405	4,290	22,300	97.6	.647
	"	9,550	4,965	4,345	21,060	98.0	.591
E....	25.7	5,540	4,300	2,580	16,000	58.3	.774
	"	5,450	4,365	2,648	15,050	59.8	.695
100-A....	61.9	15,620	5,785	7,660	32,770	176.8	.530
B....	"	16,655	6,240	7,450	30,890	172.0	.518
	48.8	11,950	5,930	6,040	26,790	138.6	.551
C.....	"	11,755	5,885	5,885	25,500	134.9	.537
	37.5	8,747	5,240	4,210	18,935	96.6	.558
D....	"	8,395	5,120	4,250	21,500	97.5	.627
E....	25.5	5,966	4,425	2,685	13,200	60.0	.621
	"	5,323	4,205	2,580	16,850	58.8	.812
101-A....	62.1	15,280	6,635	7,210	29,200	170.1	.502
B....	"	15,500	6,270	7,050	32,640	168.2	.578
C.....	"	16,000	6,530	7,410	30,150	170.9	.508
D....	49.9	14,620	5,940	5,925	24,200	136.0	.510
	"	13,080	5,830	5,610	24,950	127.9	.521
E....	"	12,300	5,930	5,760	23,830	131.8	.513
F....	37.8	9,480	5,440	4,130	18,030	93.7	.543
	"	9,200	5,130	4,100	17,700	92.9	.536
G....	"	8,910	5,340	4,120	18,220	93.1	.552
H....	26.0	5,920	4,310	2,590	13,200	58.5	.639
I.....	"	5,940	4,515	2,562	12,100	58.1	.587
	"	5,800	4,500	2,568	12,170	58.3	.589
J.....	"	5,810	4,420	2,505	12,840	57.0	.037
105-A....	62.1	16,130	6,655	7,760	29,120	177.8	.479
L....	62.3	15,735	7,100	7,705	33,895	176.8	.545
K....	"	14,710	6,838	7,450	30,630	172.3	.517
J.....	50.2	12,440	6,260	5,945	22,780	135.6	.481
I.....	"	11,890	6,314	5,874	23,605	134.0	.498
	"	....	....	5,867	25,410	134.0	.536
H....	"	12,000	6,302	5,822	25,390	132.5	.556
G....	37.7	9,550	6,563	4,214	16,700	96.2	.506
F....	"	9,260	6,546	4,214	18,820	96.0	.551
	"	9,790	6,660	4,154	10,545	98.0	.494
E....	"	10,170	6,038	4,160	16,600	95.2	.504
D....	25.9	6,045	4,552	2,681	12,055	61.2	.565
C.....	"	6,000	4,680	2,710	14,740	61.7	.673
	"	5,785	4,521	2,665	11,960	61.2	.556
B....	25.8	6,065	4,880	2,709	14,990	65.4	.692
	"	6,045	4,734	2,755	12,180	62.8	.564
106-A....	62.1	16,420	5,875	7,470	31,400	169.0	.519
B....	"	....	....	....	32,510	162.8	.569
	49.8	13,275	5,588	5,704	23,970	130.5	.519
C.....	"	11,900	5,295	5,827	26,300	121.9	.621
D....	37.6	8,835	4,800	4,200	19,545	95.7	.574
	"	8,160	4,279	4,010	19,425	91.7	.610
E....	25.7	5,680	3,880	2,496	18,440	56.6	.912
	"	5,841	3,770	2,524	14,250	57.7	.712
F....	29.8	11,111	5,091	5,498	26,180	125.0	.600
	61.9	15,940	5,896	7,485	30,620	170.5	.516
110-A....	25.7	4,580	3,694	2,572	14,100	60.4	.679
B....	"	4,470	3,644	2,392	16,260	55.9	.855
	"	4,730	3,644	2,350	14,070	54.6	.758
C.....	37.6	6,965	4,680	4,380	20,400	100.1	.575
	"	5,190	4,335	3,620	20,800	82.8	.711
	"	6,930	4,740	4,375	20,030	100.3	.567
D....	"	6,935	4,506	4,305	21,200	93.6	.614
E....	49.8	9,170	5,345	6,019	28,640	138.7	.588
F....	"	8,975	4,890	5,865	28,200	134.9	.604
G....	61.9	11,215	5,688	7,510	32,720	174.7	.539
H....	"	11,497	5,630	7,450	22,560	174.7	.549
I.....	37.5	....	....	....	....	99.5	.621
	"	....	....	....	....	97.9	.654
	"	....	....	....	....	98.5	.487
J.....	"	....	....	....	....	97.5	.563
111-A....	25.7	5,550	4,035	2,830	13,360	65.1	.582
B....	"	5,535	4,010	2,860	13,510	65.4	.575
C.....	37.6	8,250	4,880	4,330	19,570	99.0	.559
D....	"	8,375	4,855	4,435	19,740	101.1	.541
E....	49.95	11,140	5,300	6,010	26,260	137.2	.589
F....	"	10,530	5,290	6,060	29,850	138.5	.599
	"	10,900	5,810	6,020	25,640	137.8	.519
G....	61.9	14,550	5,990	7,590	29,460	173.3	.480
	"	13,800	5,740	7,660	30,390	175.2	.490
H....	"	14,080	5,965	7,800	32,430	178.9	.506
	"	13,710	5,800	7,760	31,030	177.8	.487

Results of the tests used as a basis for this report—Continued.

1,700 R. P. M.

Test No.	Barometer.	B. t. u. in exhaust.	B. t. u. in jacket.	B. t. u. in B. H. P.	B. t. u. supplied.	B. H. P.	Fuel consumption Lb./B. H. P./hr.
99-A	62.0	13,550	5,810	6,940	28,630	161.3	0.508
B	"	13,900	6,110	7,010	30,550	166.9	.531
	49.9	10,720	5,590	5,575	24,600	127.0	.551
C	"	10,550	5,470	5,480	26,070	124.9	.579
	37.6	7,420	4,860	4,065	19,630	92.4	.603
D	"	7,780	4,836	4,050	18,680	91.5	.562
E	25.7	5,070	3,900	2,532	14,280	57.2	.703
	"	5,022	4,010	2,511	13,780	56.8	.663
100-A	61.9	14,740	5,730	7,190	29,710	165.5	.513
	"	13,810	5,760	7,040	30,420	162.2	.535
B	49.8	11,760	5,640	5,530	23,090	126.7	.517
C	"	10,525	5,370	5,510	23,800	126.0	.536
	37.5	7,555	4,915	4,020	18,455	92.2	.569
D	"	8,020	4,795	3,940	16,756	90.0	.528
E	25.5	5,318	4,220	2,475	12,005	57.5	.605
	"	5,008	3,805	2,468	12,575	56.5	.631
101-A	62.1	15,840	6,240	6,650	26,990	156.6	.504
B	"	15,750	6,200	6,600	29,050	157.0	.546
C	"	14,750	5,990	6,910	28,770	159.5	.519
	49.9	12,490	5,420	5,440	21,900	124.9	.502
D	"	11,380	5,330	5,230	21,980	118.7	.506
E	"	11,950	5,700	5,330	21,400	121.7	.492
	37.8	8,430	4,890	3,950	16,470	89.5	.516
F	"	7,870	4,460	3,810	16,950	86.3	.552
G	"	7,530	4,565	3,880	16,290	87.7	.524
H	26.0	5,450	4,075	2,470	12,090	55.6	.611
I	"	5,245	4,000	2,392	11,420	54.4	.590
J	"	5,190	4,320	2,358	12,210	53.7	.644
105-A	62.1	14,500	6,240	7,078	26,090	162.0	.485
L	62.3	14,170	6,390	7,038	29,305	161.2	.516
K	"	13,950	6,592	5,961	......	136.6	......
K	"	14,010	6,392	6,959	27,250	159.0	.492
J	50.2	10,988	5,814	5,510	20,540	125.5	.468
I	"	10,605	5,912	5,440	24,360	124.0	.555
H	"	11,595	6,281	5,361	23,510	122.2	.560
G	37.7	8,750	6,242	3,987	15,535	90.4	.498
F	"	8,782	6,441	3,862	15,640	88.0	.500
E	"	9,725	4,842	3,907	15,860	89.0	.511
D	25.9	5,292	4,218	2,474	14,310	56.3	.728
	"	5,438	4,353	2,531	11,650	57.7	.578
C	"	5,265	4,239	2,515	12,040	57.3	.593
B	"	8,837	4,355	2,605	11,350	59.3	.556
106-A	62.1	13,940	5,319	6,634	30,200	151.4	.558
	"	14,840	5,415	7,138	29,120	161.2	.503
B	"	13,840	5,315	6,825	30,310	154.1	.559
	49.8	11,451	4,821	5,238	20,600	120.7	.481
C	"	......	......	5,200	22,500	118.9	.544
	37.5	7,798	4,317	3,905	19,780	89.0	.625
D	"	7,548	4,358	3,727	21,450	84.1	.733
E	25.7	5,150	3,904	2,552	13,155	55.5	.653
	"	5,080	3,436	2,333	12,560	53.3	.678
F	"	5,100	3,528	2,378	14,250	54.4	.755
110-H	61.9	10,720	5,380	7,022	29,560	162.6	.531
G	"	10,455	5,285	6,930	29,680	162.3	.529
F	49.8	8,350	4,710	5,560	24,970	127.6	.565
E	"	9,090	5,085	5,693	24,360	130.2	.528
D	37.6	6,235	4,137	4,090	19,030	93.8	.585
C	"	6,590	4,360	4,160	19,000	94.9	.564
J	"	......	......	......	......	91.3	.546
I	"	......	......	......	......	95.9	.568
	"	......	......	......	......	90.9	.508
A	25.7	4,240	3,440	2,526	13,215	59.2	.647
B	"	4,150	3,418	2,366	13,325	55.3	.708
111-H	61.9	12,640	5,470	7,205	27,340	165.1	.461
	"	12,500	5,320	7,180	27,060	164.4	.459
G	"	12,500	5,620	7,000	28,120	160.0	.496
F	49.95	10,690	5,184	5,720	23,090	130.3	.491
E	"	10,040	4,955	5,500	22,720	125.4	.511
	"	10,110	5,060	5,640	22,620	128.9	.495
	"	9,890	4,850	5,590	22,970	126.5	.511
D	37.6	7,675	4,590	4,130	17,660	94.3	.521
C	"	7,565	4,415	4,010	17,850	91.4	.550
B	25.7	5,150	3,810	2,685	12,190	61.5	.562
A	"	5,030	3,740	2,660	12,500	61.2	.580

Results of the tests used as a basis for this report—Continued.

1,500 R. P. M.

Test No.	Barometer.	B. t. u. in exhaust.	B. t in Jacket.	B. t. u. in B. H. P.	B. t. u. supplied.	B. H. P.	Fuel consumption Lb./B. H. P./hr.
99-A....	62.0	10,270	5,495	6,205	28,100	144.0	0.464
	"					145.1	
	"	11,730	5,498	6,255	27,060	144.0	.528
B....	49.9	9,300	5,100	5,005	20,700	114.0	.515
C.....	"	9,120	5,125	5,605	21,820	113.7	.532
	37.6	6,410	4,670	3,600	15,920	82.2	.551
D....	"	6,840	4,320	3,625	16,050	82.0	.540
E....	25.7	4,390	3,504	2,334	12,550	52.7	.671
	"	4,390	3,525	2,265	12,100	51.3	.651
100-A....	61.9	13,230	5,900	6,490	25,220	160.0	.482
	"	11,570	5,000	6,180	27,650	142.2	.555
B....	49.8	9,779	4,975	4,930	20,905	118.0	.526
C.....	"	9,501	4,875	4,930	21,720	115.5	.541
	37.5	6,538	4,270	3,528	20,280	80.9	.713
D....	"	7,178	4,270	3,575	14,495	81.8	.503
	25.5	4,518	3,210	2,265	10,800	51.9	.591
E....	"	4,634	3,470	2,230	10,970	50.8	.610
101-A....	62.1	13,300	5,490	6,010	26,410	142.5	.546
	"	13,240	5,750	5,980	24,410	141.5	.507
B....	"	11,510	5,390	5,850	32,300	138.1	.684
	"	12,950	5,460	5,900	25,200	137.0	.529
C.....	"	12,590	5,430	5,990	25,450	137.3	.529
	49.9	11,040	4,950	4,850	21,030	111.0	.541
D....	"	10,410	5,020	4,870	18,860	110.8	.536
	"	10,260	4,955	4,830	19,680	109.9	.522
E....	"	9,780	5,200	4,785	18,740	107.5	.486
	37.8	6,730	4,055	3,585	15,100	81.2	.523
F....	"	5,660	3,590	3,470	15,750	78.7	.563
G....	"	6,115	5,620	3,480	15,640	79.0	.561
	"	6,670	4,595	3,460	14,720	78.0	.531
H....	26.0	4,840	3,725	2,245	11,020	50.7	.613
	"	4,510	3,620	2,200	11,210	50.0	.633
I.....	"	4,550	3,675	2,150	11,480	48.8	.665
	"	4,320	3,684	2,161	11,380	49.2	.653
105-A....	62.1	12,440	5,580	6,290	27,880	144.0	.566
	"	11,910	5,448	6,060	......	139.0	......
	63.2	11,560	5,531	6,300	23,490	144.5	.577
	"	11,825	5,580	6,260	24,290	143.2	.494
L.....	"	11,960	5,920	6,280	26,495	144.5	.521
K....	"	11,770	5,540	6,118	......	140.0	......
	"	11,310	5,645	6,199	28,220	141.5	.572
J	50.2	9,390	5,162	4,928	19,560	112.0	.499
I.....	"	9,100	5,160	4,846	22,540	110.8	.576
H....	"	10,040	5,112	4,840	22,060	110.0	.563
	"	9,820	5,199	4,850	21,430	110.5	.564
G....	37.7	6,160	5,582	3,523	14,160	80.2	.513
F....	"	7,050	4,840	3,479	......	79.3	......
	"	7,270	4,563	3,538	14,440	80.5	.506
E....	"	8,599	4,842	3,479	14,145	79.2	.511
D....	25.9	4,577	3,720	2,241	10,875	51.2	.609
C.....	"	4,360	3,678	2,284	11,080	52.1	.599
B....	"	7,429	3,760	2,220	10,920	53.4	.601
106-A....	62.1	12,290	4,915	6,325	28,020	143.1	.547
	"	12,080	4,873	6,191	26,500	140.2	.539
B....	49.8	9,382	4,230	4,861	22,190	111.2	.563
	"	9,680	4,495	4,695	25,800	107.3	.692
	37.5	6,230	3,761	3,523	15,850	80.2	.556
D....	"	7,105	4,274	3,500	16,710	79.8	.602
E....	25.7	4,235	3,198	2,238	12,280	50.7	.678
	"	4,339	3,250	2,206	13,165	50.5	.758
H....	61.9	9,230	5,182	6,175	25,280	143.0	.516
G....	"	9,095	4,940	6,143	25,250	142.6	.508
F....	49.8	7,135	4,276	5,110	22,780	117.4	.560
E....	"	7,670	4,625	5,240	21,640	119.8	.510
D....	37.6	5,670	3,894	3,784	16,870	86.7	.561
C.....	"	5,960	3,930	3,750	16,680	85.5	.550
I.....	"	......	......	......	......	85.8	.499
J.....	"	......	......	......	......	81.9	.528
B....	25.7	3,545	3,050	2,344	12,380	54.5	.665
	"	3,694	3,090	2,275	11,700	53.3	.636
111-H....	61.9	10,930	4,935	6,390	25,090	146.0	.477
G....	"	10,840	5,060	6,080	25,750	138.5	.523
	"	10,420	4,860	6,200	25,850	141.2	.506
F....	49.95	8,980	4,695	5,070	20,480	115.8	.486
E....	"	8,480	4,500	4,870	21,080	111.0	.535
D....	37.6	6,475	4,190	3,695	15,650	84.1	.515
C.....	"	6,300	4,100	3,525	15,220	80.4	.532
B....	25.7	4,530	3,380	2,432	10,795	55.8	.540
A....	"	4,450	3,380	2,380	10,650	55.1	.551

Results of the tests used as a basis for this report—Continued.

1,300 R. P. M.

Test No.	Barometer.	B. t. u. in exhaust.	B. t. u. in jacket.	B. t. u. in B. H. P.	B. t. u. supplied.	B. H. P.	Fuel consumption Lb./B. H. P./hr.
99-A.....	62.0	8,950	3,770	5,250	26,200	122.0	0.622
	"	10,800	4,740	5,210	23,880	120.7	.559
B....	49.9	7,610	4,660	4,210	17,620	96.2	.522
C.....	"	7,690	4,440	4,225	18,470	96.3	.583
	37.6	5,800	4,040	3,030	13,030	69.1	.587
D....	"	5,060	2,686	3,010	13,140	66.0	.533
	25.7	3,680	3,360	1,695	9,860	44.4	.627
E....	"	3,650	3,265	2,000	10,280	45.1	.627
100-A....	61.9			5,570		128.5	.488
	"	9,660	4,635	5,320	23,990	122.6	.557
B....	49.8	8,225	4,415	4,200	17,020	96.5	.504
	"	7,792	4,340	4,255	18,225	98.0	.531
C.....	37.5	5,345	3,695	3,030	15,760	69.6	.646
D....	"	5,708	3,780	3,024	12,615	69.1	.518
	25.5	4,150	3,260	1,963	10,560	45.0	.666
E....	"	4,390	2,790	1,892	7,148	43.3	.469
101-A....	62.1	10,880	5,120	5,110	19,990	120.9	.486
B....	"	10,450	4,740	4,890	20,100	116.3	.509
C.....	"	10,890	4,880	5,260	21,700	120.5	.513
	49.9	8,280	4,345	4,130	17,070	97.1	.515
D....	"	8,410	4,320	4,130	17,400	93.9	.483
E....	"	8,140	4,620	4,160	17,390	94.9	.518
	37.8	5,900	4,040	3,010	13,940	68.6	.575
F....	"	6,180	3,870	2,970	13,950	67.4	.582
G....	"	6,460	4,560	2,930	12,170	66.5	.519
	"	6,940	4,775	2,920	12,720	65.9	.543
H....	26.0	4,080	3,325	1,940	8,715	43.8	.560
	"	3,840	3,265	1,920	10,200	43.3	.663
	"	3,820	3,220	1,905	9,570	43.1	.623
I....	"	3,570	3,020	1,810	10,700	41.1	.734
	"	3,605	3,270	1,845	9,810	42.0	.660
105-A....	62.1	9,750	4,845	5,396	22,860	122.2	.541
	62.3	9,925	5,168	5,543	23,100	127.6	.531
L....	"	10,605	5,402	5,520	22,020	126.5	.492
K....	"	10,140	4,960	5,420		123.9	
	"	10,020	5,070	5,430	25,580	124.5	.592
J.....	50.2	7,821	4,624	4,173	18,460	95.4	.556
I.....	"	7,450	4,547	4,210	19,840	95.3	.569
H....	"	8,140	4,512	4,132	16,920	94.2	.522
	"	7,701	4,699	4,166	18,180	95.2	.557
105-G....	37.7	5,762	4,055	3,019	11,910	68.8	.503
F....	"	5,812	4,235	3,040	13,240	69.8	.598
E....	"	6,155	4,101	2,920	12,940	66.5	.557
D....	25.9	3,740	3,376	1,892	9,560	43.3	.636
C.....	"	3,558	3,283	1,932	9,635	44.1	.619
B....	"	5,895	3,356	1,960	9,721	45.3	.627
	"	3,737	3,356	1,990	9,920	44.6	.636
106-A....	62.1	10,290	4,390	5,585	24,560	125.1	.548
	"	10,380	4,537	5,450	25,115	123.3	.580
B....	49.8	7,585	3,857	4,280	20,745	96.5	.606
C.....	"	8,060	4,104	4,067	17,500	93.1	.541
	37.5	5,218	2,913	3,104	16,170	70.7	.643
D....	"	6,025	3,760	2,963	14,010	68.3	.590
	25.7	3,860	3,420	1,945	9,238	44.3	.586
E....	"	3,928	3,062	1,878	11,880	42.6	.799
110-H....	61.9	7,992	4,383	5,180	19,770	119.5	.482
G....	"	7,665	4,330	5,260	22,650	121.2	.580
H....	"					121.3	.491
F....	49.8	6,320	3,980	4,220	18,450	97.1	.549
	"	6,635	4,050	4,327	21,010	99.2	.600
	"	6,850	4,105	4,486	19,410	103.2	.535
D....	37.6	4,960	3,480	3,172	13,980	72.6	.554
J.....	"					69.9	.561
C.....	"	4,750	3,914	3,136	18,460	71.5	.530
B....	25.7	3,340	3,024	1,958	10,325	45.8	.663
A....	"	3,084	2,676	1,919	10,000	44.9	.644
111-H....	61.9	9,290	4,455	5,300	21,800	121.4	.500
	"	9,315	4,340	5,420	21,740	123.7	.483
G....	"	10,090	4,350	5,300	22,320	118.6	.580
F....	49.95	7,185	4,050	4,260	17,320	97.5	.492
E....	"	7,685	3,990	4,070	17,850	92.9	.541
D....	37.6	5,625	3,620	3,162	14,000	72.4	.539
	"	5,750	3,666	3,150	13,170	72.0	.510
C.....	"	5,100	3,545	3,030	13,080	69.0	.584
B....	25.7	3,838	3,210	2,095	9,470	48.0	.551
A....	"	3,812	2,982	2,042	9,530	47.7	.579